OPTIMIZING FEEDSTOCK LOGISTICS AND ASSESSMENT OF HYDROLOGIC IMPACTS FOR SUSTAINABLE BIO-ENERGY PRODUCTION

A Dissertation

by

MI AE HA

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ABSTRACT

Rising world petroleum prices and global warming are contributing to interest in renewable energy sources, including energy produced from agricultural crops and waste sources of biomass. A network of small mobile pyrolysis units may be the most cost effective system to convert biomass from agricultural feedstocks to bio-crude oil. Mobile pyrolysis units could be moved to the feedstock production fields thereby greatly simplifying feedstock logistics. In the North Central (NC) region of the U.S., possible feedstocks are corn stover, energy sorghum, and switchgrass. A grid-based Geographic Information System (GIS) program was developed to identify optimum locations for mobile pyrolysis units based on feedstock availability in the NC region. Model builder was used to automate the GIS analysis. Network analysis was used to find the best route to move the mobile pyrolysis units to new locations and to identify the closest refinery to transport the bio-crude oil.

To produce bioenergy from feedstocks, the removal of biomass from agricultural fields will impact the hydrology and sediment transport in rural watersheds. Therefore, the hydrologic effects of removing corn stover from corn production fields in Illinois (IL) were evaluated using the Soil Water Assessment Tool (SWAT). The SWAT model was calibrated and validated for streamflow and sediment yields in the Spoon River basin in IL using observed data from the USGS. The modeling results indicated that as residue removal rates increased, evapotranspiration (ET) and sediment yields increased, while streamflows decreased.

Biochar is a carbon-based byproduct of pyrolysis. To ensure that the mobile pyrolysis system is economically and environmental sustainable, the biochar must be land applied to the feedstock production fields as a soil amendment. An assessment of hydrologic changes due to the land application of biochar was made using the SWAT model in the Spoon River basin and changes in soil properties due to incorporation of biochar into the soil obtained from laboratory experiments by Cook et al. (2012). Model simulations indicated that a biochar application rate of 128 Mg/ha decreased water yield, and sediment yield in surface runoff and increased soil moisture and ET.

DEDICATION

To my parents

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The First and foremost, I would like to thank my advisor Dr. Clyde Munster for his wonderful guidance, motivation and constant encouragement. Without his patience, constructive comments and feedback, it would have been impossible to handle my research. I would also like to extend my sincere thanks to my committee members Dr. Tony Provin, Dr. Raghaven Srinivasan, and Dr. Patricia Smith for their participation in my dissertation committee and their valued opinions and feedback.

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CHAPTER I

INTRODUCTION

Renewable energy is getting a lot of interest as a good way to provide clean energy and to reduce the negative effects of greenhouse gas (GHG) emissions on the environment. Pyrolysis is a thermal conversion process for converting feedstocks and other carbon-based materials to bio-oil, synthesis gas (syngas), and biochar. Mobile pyrolysis units are an effective way to convert low density agricultural feedstocks to high density bio-oil thereby reducing transportation costs. The possible feedstocks in the North Central (NC) region are corn stover, energy sorghum, and switchgrass. A Geographic Information System (GIS) program was developed to find optimum locations for mobile pyrolysis stations based on feedstock availability. The GIS program also calculated feedstock hauling distances to the pyrolysis station and the hauling distances required to transport biochar back to feedstock production fields. In addition, the GIS program found the optimum routes to transport the bio-oil from the pyrolysis station to the closest refinery and the optimum routes to move the mobile pyrolysis unit from station to station.

The Soil Water Assessment Tool (SWAT) simulation was used to assess changes in hydrology, sediment transport, and crop production in the Spoon River Basin. The hydrologic impacts of four different residue removal rates (25%, 50%, 75%, and 100%) were investigated using SWAT. Biochar, a byproduct of pyrolysis, was applied to feedstock production fields as a soil amendment to produce feedstocks sustainably.

Based on results of laboratory experiments, soil properties were incorporated with the SWAT modeling in the Spoon River Basin.

Objectives of Research

The objectives of research are as follows:

1. Develop a GIS program to identify optimum locations for mobile pyrolysis units in the North Central (NC) region of the U.S to produce bioenergy using agricultural feedstocks.
2. Use the GIS program to identify optimum locations based on feedstock availability for mobile pyrolysis stations in the NC region to convert corn stover, energy sorghum, and switchgrass to bioenergy. Then use the GIS program to calculate, 1) feedstock hauling distance to the pyrolysis station and biochar hauling distance back to the feedstock production fields, 2) the optimum route and distance required to transport bio-oil from the pyrolysis station to the nearest oil refinery, and 3) the optimum routes and distances required to move the mobile pyrolysis unit from station to station..
3. Evaluate the hydrologic impacts of removing biomass from agricultural fields for bioenergy using the SWAT model.
4. Evaluate the impacts of biochar incorporation into the soil at feedstock production fields on hydrology, sediment yields, crop yields, and nutrient transport in surface runoff using the SWAT model.

Organization of Dissertation

This dissertation consists of six chapters. Chapter I is an introduction, which explains research objectives and organization of the dissertation. Chapter II details the development of a GIS program to optimize feedstock logistics for bioenergy production by mobile pyrolysis units. Chapter III presents results from the GIS program when it was used to optimize feedstock logistics for mobile pyrolysis units in the NC region of the U.S. for corn stover, energy sorghum, and switchgrass feedstocks. Chapter IV presents an assessment of residue removal from agricultural fields for bioenergy production on hydrology, sediment transport, and crop production. Chapter V evaluates the impacts of biochar application to agricultural soils on hydrology, sediment transport, crop yields, and nutrient transport.

Each chapter in this dissertation will be submitted to a journal paper for publication. Therefore each chapter will have its own introduction, literature review, methods, results, and conclusion sections.

CHAPTER II

A GEOGRAPHIC INFORMATION SYSTEMS PROGRAM TO OPTIMIZE FEEDSTOCK LOGISTICS FOR BIOENERGY PRODUCTION FOR MOBILE PYROLYSIS UNITS

Synopsis

The goal of this research project was to develop a comprehensive decision making tool to optimize the use of a fleet of mobile pyrolysis units in the North Central (NC) U.S. to produce bio-oil from agricultural feedstocks. The concept is to use mobile pyrolysis units to convert low density biomass to high density bio-oil to minimize the cost of feedstock logistics. The feedstocks evaluated in this project included corn stover, energy sorghum, and switchgrass. It was assumed that energy sorghum would replace grain sorghum and switchgrass would be grown on land in the conservation reserve program (CRP). A Geographic Information System (GIS) program was developed to optimize the movement of mobile pyrolysis units based on an analysis of transportation networks, cropping patterns, feedstock production rates, and oil refinery locations in the NC region. The locations of existing corn, sorghum, and CRP fields in the NC region were obtained from the cropland data layer (CDL) database from the National Agricultural Statistics Service (NASS). Model builder was used to automate the GIS procedures. Network analyst, an extension of ArcGIS, was used to find the best route to move the mobile pyrolysis units to new locations and to identify the closest refinery to receive the bio-crude oil. The mobile pyrolysis unit feedstock input rate was assumed to

be 40 tons/day. The GIS program was integrated with a stochastic economic model to assess bio-oil production costs. A sensitivity analysis of the economic model showed feedstock costs were reduced to $19.90/tons with 90% or higher probability of a positive net present value.

Introduction

Increasing world gas prices and global warming are contributing to interest in renewable energy sources, including energy produced from crop residues. Pyrolysis is a thermal conversion process for converting agricultural residues and many other carbon-based materials into bio-energy. The mobile pyrolysis system converts diverse feedstocks to bio-crude oil, synthesis gas, and biochar. Corn stover, energy sorghum, and switchgrass are possible feedstocks for pyrolysis in the North Central (NC) region. The goal of this study was to find optimal locations to station mobile pyrolysis units and to minimize feedstock transportation costs. To accomplish this goal, a GIS program was developed to optimize feedstock logistics for the production of bio-oil using mobile pyrolysis units. The GIS analysis provided, (1) optimum locations for mobile pyrolysis stations based on feedstock availability, (2) feedstock hauling distances from the fields to the mobile pyrolysis unit as well as biochar hauling distances back to feedstock production fields, (3) optimum routes to move the mobile pyrolysis units from station to station, and (4) the optimum routes to transport the bio-oil to the closest refinery. Model Builder was used to automate GIS processes and to produce an automated model with limited manual inputs. Network Analysis was used to search for optimum routes to haul feedstocks from one mobile pyrolysis location to the next and from the pyrolysis stations to the closest refineries. Due to the many constrains that affect the production of bio-oil by a centralized plant using agricultural feedstocks, such as weather, that affects feedstock production and feedstock hauling costs, mobile pyrolysis units have many advantages. Mobile pyrolysis units are more flexible than centralized pyrolysis units and the therefore better able to overcome these constrains.

Study area

This GIS project analyzed feedstock logistics for mobile pyrolysis units in the NC U.S. (see Figure 2.1). The location of feedstock areas planted in the NC region and grain yields and production rates were obtained from NASS.

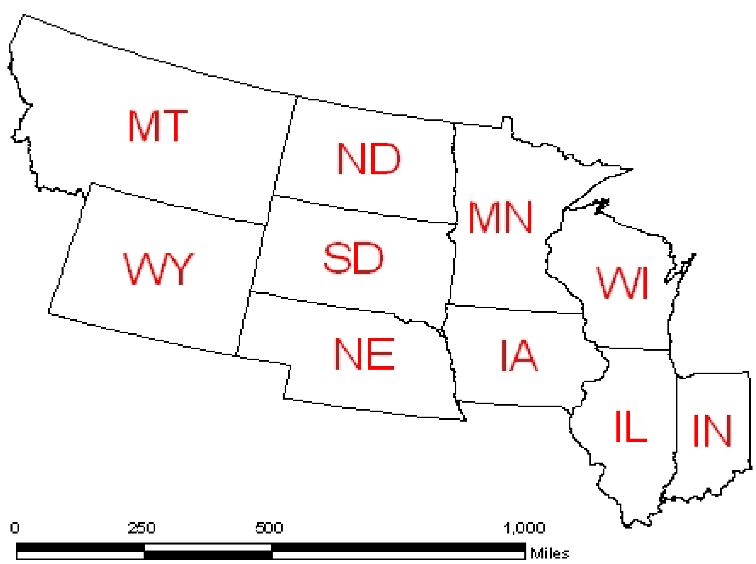


Figure 2. 1 The states in the North Central region of the U. S. included in this feedstock logistic study for mobile pyrolysis units.

The GIS program optimized the movement of mobile pyrolysis units in the NC region to minimize feedstock transportation costs. The GIS program automated the following procedures:(1) Identified optimum locations for mobile pyrolysis stations based on feedstock availability, (2) Assessment of feedstock hauling distances from production fields to a mobile pyrolysis station, (3) Determination of optimum routes to move the mobile unit from one pyrolysis station to the next station, (4) Determined the distance to move biochar back to production fields, and (5) Determination of optimum routes to transport the bio-oil from the pyrolysis station to the nearest oil refinery.

Pyrolysis

Pyrolysis is the thermal degradation of biomass in the absence of oxygen. During pyrolysis, the feedstocks are heated to temperatures of 400-600 degrees Celsius and converted to bio-oil, synthesis gas (syngas), and bio-char. The fast pyrolysis system produces mostly bio-oil that may be upgraded to transportation fuels with smaller quantities of biochar and syngas *(Brown et al., 2011)*. The pyrolysis process requires drying and grinding of the feedstock to increase heat transfer rates. After the feedstock is dried and ground, it is rapidly heated to high temperatures to produce the vapors, aerosols, and biochar. The vapors and aerosols are then cooled and condensed forming bio-oil *(Bridgwater et al., 1999)*. The fast pyrolysis used six steps for conversion of biomass to transportation fuels: (1) pre-treatments (drying biomass to 7% moisture content and grinding it to a final particle size diameter of 3 mm), (2) pyrolysis (fluidized bed reactor operation at 450 degrees Celsius and atmospheric pressure in oxygen-free environment), (3) solids removal (biochar), (4) oil recovery (indirect heat exchanger and an electrostatic precipitator to collect condensable vapors), (5) heat generation, and (6) hydro processing *(Brown et al., 2011)*. Numerous agricultural crops can be used in the pyrolysis method including corn stover, sorghum, switchgrass, rice, wheat, sugar cane, straw and miscanthus *(Mohan et al. 2006)*. The bio-oil product is typically a dark brown, organic liquid with high oxygen content *(Czernik and Bridgwater, 2004)*. Biochar is a charcoal like substance that is a by-product of the pyrolysis process. The second highest yielding production for slow and fast pyrolysis systems is biochar, typically in the range of 15-40% on a weight basis of the biomass feedstock *(Brown et al., 2011)*. Biochar additions to soils may mitigate some of the negative effects of removing crop residues from production fields and enhance soil quality. Applying the biochar to the soil replaces carbon, nitrogen and most of the plant nutrients which are removed from the soil with the biomass *(Mullen et al., 2010)*. The gases that cannot be condensed are known as synthesis gas or syngas. Syngas is mostly carbon monoxide and hydrogen and can be used to generate electric power.

Mobile pyrolysis

This project assesses the use of a mobile pyrolysis system to produce transportation fuels in the NC U.S. Mobile pyrolysis units have many advantages over large centralized pyrolysis plants. The mobile pyrolysis units can be deployed directly to the feedstock production fields thereby minimizing feedstock hauling distances. Agricultural feedstocks commonly have low bulk densities that range from 40 to 200 kg

m^{-3} *(Adapa et al., 2011)* and high water contents from10 to 85% *(Propheter et al., 2010)*. The mobile pyrolysis station requires space for temporary storage of feedstocks, bio-oil, and biochar and room for large tractor trailers to maneuver. The mobile pyrolysis unit converts the energy in the feedstock into a high density bio-oil. Therefore, transporting bio-oil long distances to an oil refinery is most cost effective than transporting low density feedstocks long distances to a centralized pyrolysis plant. In addition the syngas produced during pyrolysis can be used to dry the feedstocks and to power the pyrolysis equipment. The biochar byproduct is also a low density material that cannot be transported long distances cost effectively. Therefore, mobile pyrolysis unit also facilitate the land application of biochar back to feedstock production fields. The mobile pyrolysis unit in this study was assumed to be a fluidized bed system 30.48 cm in diameter operating at a feedstock rate of 40 tons per day with a 10% or less moisture content. This system would produce bio-oil at a rate of 50 gallons per ton of feedstock and a biochar production rate of 10 tons per day *(S. Capareda, personal communication, 2009)*.

Feedstocks

The feedstocks used in this study were corn stover, energy sorghum and switchgrass. Corn stover was chosen because of its high production rates throughout the NC region. The energy sorghum was selected for analysis because it was designed specifically for high biomass production for bio-fuels. It was assumed that energy sorghum would be planted in fields where grain sorghum is now grown. Switchgrass was evaluated since it could be grown on poor soils often found in the CRP and would not displace agricultural crops. Corn stover biomass (lb) was calculated using equation 1.

Corn stover biomass = 10 year average corn yield (bu/ac) x 56 (lbs/bu) x 0.25 x area (ac) Eq. 2.1

The ratio of corn for grain (kg) and corn stover (kg) assumed 1:1 and one bushel of corn was assumed to be 25.4 kg (56 lbs) *(USDA, 2010b)*. However, only 25% of the corn stover was made available as a feedstock for pyrolysis, leaving 75% of corn stover in the field for erosion prevention and soil improvement. Energy sorghum was assumed to yield approximately 5.6 Mg/ha with 100% available for harvest *(Baltensperger, 2012)*. For switchgrass, mean annual switchgrass yields were 2.24 Mg/ha for western Nebraska *(Baltensperger, 2012)*.

Biochar utilization

One possible use of the biochar is to return it to the feedstock production fields as a soil amendment. Biochar contains nutrients which potentially could be utilized for feedstock production. Crop residues contain substantial amounts of plant nutrients such as, C, N, K, P, Ca, and Mg and some of these nutrients end up in the biochar *(Laird, 2008)*. However, crop growth may be reduced when there are very high applications of biochar *(Lehmann et al., 2006)*. Application of biochar to soils is hypothesized to increase water holding capacity, build soil organic matter, improve nutrient cycling, lower bulk density, and reduce transport of pesticides and nutrients to surface and ground water *(Laird, 2008)*. A sustainable feedstock production system for bioenergy production will require that biochar be land applied back to the production fields.

Literature Review

GIS analyses have been used in many previous bioenergy studies. *Singh et al. (2008)* studied agricultural biomass potential for power production in the Indian state of Punjab. The spatial study concluded that the costs of collection and transportation of feedstocks were important for sustainable biomass energy conversion facilities. Biomass feedstock collection and transportation costs could be reduced by locating the biomass power plants near biomass collection centers. In addition, spatial information technologies led to more scientific planning in bioenergy power plant construction. Shi et al. (2008) presented a case study of using remote sensing and GIS to evaluate the feasibility of setting up biomass power plants and optimizing the plant location in Guangdong, China. Vegetation type, ecological retaining, economic conditions, and harvest costs were considered in the study that used MODIS/Terra remote sensing data. The GIS program was used to assess feedstock transportation distances along roads.

In another GIS study, historic crop yields were estimated for 10 sites in the Peace River region of Alberta, Canada. This study determined inter-year variability of biomass availability by quantifying the feedstock supply risk to ensure future crop productivity *(Stephen et al. 2010)*. Biomass availability was assessed as a function of grain yield, biomass-to-grain ratio, cropping frequency, and residue retention rate. *Stephen et al. (2010)* found the availability of feedstock quantities were highly dependent on biomass-to-grain ratio and developed a methodology for determining the range of biomass availability. A spatially explicit Bioenergy Sitting Model (BSM) of the bioenergy production system in California was developed by *Tittmann et al. (2010)*. This work expanded on previous bioenergy siting work by optimizing the system using spatially explicit feedstock supply curves, multiple potential conversion technologies and geographically determined bioenergy demands. The model combined a spatial model with economic aspects of bioenergy production systems, and used a transportation network GIS analysis with a mixed integer-linear programming (MIP) optimization model. *Beccali et al. (2009)* used a GIS-based methodology to evaluate the energy potential of biomass from the agricultural and forestry sectors in Sicily. The GIS program considered all the transportation components for the bioenergy production, including proximity to streets, morphology and elevation of terrain, density of facilities, and other factors. *Ma et al. (2005)* produced a siting suitability map identifying the most suitable locations for distributed bio-energy systems using dairy manure in Tompkins County, New York. The GIS model integrated both spatial and non-spatial data. The GIS model found availability of renewable energy resources based on the distribution of dairy farms. *Perpina et al. (2009)* used a grid concept for an optimal use of agricultural and forest residue. Potential sites for obtaining biomass energy and optimal locations for bioenergy plants were mapped to calculate the amount of residue within a rectangular area of 1 km^2 in Valencia, Spain, using ArcGIS. In addition, GIS technology was used to identify potential locations in the Midwestern region for the collection and storage of corn stover *(Haddad and Anderson, 2008)*. This study included the following steps: (1)

site selection criteria, (2) identification of study area and service area based on the transportation Network Analysis, (3) reclassification of spatial layers, (4) overlaying the reclassified spatial layers with equal weights to produce the two main models, and (5) overlaying the main models using different weights. The centroid point concept was used to determine the route from each cotton field to the closet gin in Lubbock County, Texas *(Simpson et al., 2007)*. The transport routine used the local, county and state roads. *Frombo et al. (2009)* used a GIS-based Environmental Decision Support System (EDSS) to define planning and management strategies for the optimal logistics for energy production from wood residues. The EDDS was divided in three modules, 1) GIS, 2) data management system, and 3) the optimization (decision problems such as strategic planning, tactical planning, and operational management). A two-stage methodology was used to identify the optimum location for the facility using woody biomass in the Village of L'anse in Baraga County of the Upper Peninsula of Michigan. Stage I used a GIS approach to identify feasible biofuel facility locations based on railroad and road transportation networks, county, city and village boundaries, a population densities, and pulpwood production locations. Stage II selected the preferred location using a total transportation cost model *(Zhang et al., 2011)*.

Methods

A GIS program was developed to determine the optimum locations for mobile pyrolysis units in the NC region based on the feedstock availability. Mobile pyrolysis unit move times were assumed to be 1, 2, 4, 6, 8, 10, and 12 month intervals. Feedstock availability was systematically calculated throughout the region using a square overlay grid. ArcGIS was used to combine crop yields, physical field locations and grid layers to define available biomass in each grid cell based on mobile pyrolysis move times. Corn, sorghum, switchgrass (CRP lands) field were obtained from 2008 Cropland Data Layer (CDL) from the National Agricultural Statistics Service (NASS). The data provided were raster files, which were converted to shape files. The average crop yields were based on the 10 average yield of each county. The ten year average (1999 to 2008) from NASS was used to determine the amount of corn stover available for pyrolysis. Energy sorghum and switchgrass were assumed to yield approximately 5.6 Mg/ha and 2.24 Mg/ha for western Nebraska with 100% available for harvest *(Baltensperger, 2012)*. It was assumed that the mobile pyrolysis units were located in the center of the grid cell. Therefore, the average distance required to transport feedstock to the mobile pyrolysis unit and biochar back to the feedstock production fields was one half the gird cell size.

Model builder was used to automate these GIS procedures. The user selected the optimum mobile pyrolysis station locations based on the GIS results for feedstock availability for each scenario. The mobile pyrolysis unit could be moved at different time steps; 1, 2, 4, 6, 8, 10, and 12 month time intervals. Once the locations of the mobile pyrolysis stations were identified, the shortest routes between optimum locations were determined using county level roads and streets obtained from the U.S. Census Bureau ftp server available at ftp://ftp2.census.gov/geo/tiger/. These line and point files were used as input for the ArcGIS extension Network Analysis. Network Analysis was used to calculate distances from one mobile pyrolysis station to the next station.

Distances to the closest oil refineries were also calculated. ArcGIS Model Builder was then used to automate these GIS procedures. The final GIS table including feedstock hauling distances, distances from one station to next station, and distances to the closest oil refineries were imported to the economic model. The stochastic economic model analyzed the economic potential of the mobile pyrolysis unit based on feedstocks, locations, and different movement times. The economic model was integrated with the GIS analysis to identify optimum pyrolysis locations based on probabilities of potential returns on investment.

Input layers

The locations where corn and sorghum fields planted in the NC region were obtained from the 2008 cropland data layer (CDL) database from the spatial analysis research section of NASS *(USDA, 2010a)*. NASS annually provides the CDL with crop specific digital data layers in GIS raster formats *(USDA, 2010a)*. The CDL program uses imagery from the Resourcesat-1 AWiFS and the Landsat 5 TM satellites, which produces digital categorized geo-referenced images exported to GeoTiff format for use in the ArcGIS interface. The University of Illinois at Urbana-Champaign Institute of Natural Resources Sustainability performed the CDL accuracy assessment of the remote sensing applications. Their analysis found the strong evidence of land cover classification success with 97.6% accuracy and a corresponding omission error of only 2.4% and an overall kappa coefficient of 0.95 *(Luman and Tweddale, 2008)*. The CDL raster data for corn and sorghum fields planted in the NC region were converted to polygon shape files to identify feedstock locations.

The transportation networks in the NC region were used to optimize feedstock logistics. A network database that contains all of the interstate highways, major roads, and local roads in the NC region was developed. The road network data was available from the U.S. Census Bureau Geography at ftp://ftp2.census.gov/geo/tiger, which provides ArcGIS formatted roads and streets on a county basis. A shape file with county level roads and streets was obtained from the U.S. Census Bureau ftp server at ftp://ftp2.census.gov/geo/tiger/TIGER2007FE. Major highways and local roads were merged to create the transportation system using “append” function in ArcGIS. The appended road lines were used as an input for the Network Analysis in the ArcGIS extension to create the road networks.

Grid cells

A GIS program created a square grid that overlaid the entire NC region. The feedstock availability was calculated for each grid cell using the following methodology. First, a square grid was developed and the size of the grid cells was based on pyrolysis unit move times. For example, a move time of 6 months requires more feedstock and therefore a larger grid cell than a 2 month move time. Then the area of the feedstock fields in each grid cell was determined using polygon shape files of planted fields (2008) from NASS *(USDA, 2010b)*. The grid and feedstock shape files were merged and shape files that overlapped multiple grid cells were subdivided into shape files that do not overlap multiple cells. Then the amount of available corn stover in each grid cell was calculated by multiplying the feedstock area by the 10 year (1999 to 2008) average production rates (on a county basis) from NASS Quick Stats 1.0 *(USDA, 2010b)*. For energy sorghum, the feedstock production rate for energy sorghum was 13,388 lbs/ac with the basic assumption of 100% harvest. Mean annual switchgrass yields of 6.30 Mg/ha for Nebraska, South Dakota and North Dakota was reported by *Kiniry et al. (2008)*. Figure 2.2 demonstrates the GIS methods for creating and merging the grid with corn field locations. The grid cell was overlain over the feedstock shape files and the feedstock production area was calculated in each grid cell.

(A) Grid (B) Feedstock locations (C) Merged grid and feedstock locations

Figure 2. 2 The GIS methods that were used to calculate feedstock availability for mobile pyrolysis units using the following methods, (A) a square grid was developed, (B) planted feedstock fields as polygon shape (raster files converted to vector files) files from NASS were used, and (C) the grid and feedstock shape files were merged and shape files that overlapped multiple grid cells were subdivided into shape files that do not overlap multiple cells.

Corn stover

Crop yields on a county basis were obtained from NASS *(USDA, 2010b)* and used in this study. For example, the 10 year average (1999 to 2008) for corn for grain in LaSalle County was 164 bushel/acre and it was assumed that one bushel of corn grain weighed 56 pounds *(USDA, 2010b)*. Therefore for LaSalle County average grain production of 9,182 lbs/ac was used. It was also assumed that one pound of corn grain was equal to one pound corn of stover biomass *(Pordesimo et. al, 2004)*. However, only 25% of the corn stover was made available for the pyrolysis units leaving 75% on the land to protect against erosion and to improve the soil. Therefore, an average of 2,295 lbs/ac of corn stover was assumed to be available as a feedstock for the mobile pyrolysis units in LaSalle County, IL. Since the mobile pyrolysis unit utilizes feedstock at a rate of 80,000 lbs/day at 10% moisture content, this is equivalent to a utilization rate of 34.85 ac/day (80,000 lbs/day ÷ 2,295 lbs/ac). On an annual basis, the area of corn stover required to supply a mobile pyrolysis unit for one year in LaSalle County was 12,721 acres (34.85 ac/day x 365 days). Several move time scenarios (1, 2, 4, 6, 8, 10, and 12 months) were applied to the mobile pyrolysis units. Average crop yields and grain production rates as well as corn stover acreage required to supply mobile pyrolysis units for various move times were calculated in the GIS analysis for the entire NC region.

Energy sorghum

It was assumed that a high biomass cultivar of sorghum (bioenergy sorghum) would be grown in fields where grain sorghum is currently planted in the NC region.

The basic assumption for bioenergy sorghum is that 100% would be harvested each year. The biomass production rate was assumed to be 5.6 Mg/ha (2.5 tons/acres) *(Baltensperger, 2012)*. Therefore, based on a production rate of 5.6 Mg/ha the mobile pyrolysis unit utilizes 16.0 ac/day of sorghum feedstock (80,000 lbs/day ÷ 4,996 lbs/ac) and the area of bioenergy sorghum required to supply a mobile pyrolysis unit for one year was 5,844 acres (16.0 ac/day x 365 days). The area of bioenergy sorghum required to supply a mobile pyrolysis unit for move times of 1, 2, 4, 6, 8, and 10 months was calculated using 16.0 ac/day.

Switchgrass

Switchgrass is one of the possible feedstocks in this study, but there is very little switchgrass now grown in the U. S. However, some of the Conservation Reserve Program (CRP) lands and in the NC region may be a good source for a switchgrass to be grown in future. The CRP protects millions of acres of American topsoil from erosion and is designed to safeguard the Nations' natural resources *(USDA, 2011)*. In general, perennial dry land forages in the region were less than 2.24 Mg/ha (1 ton/acre) and this value was used for switchgrass yields *(Baltensperger, 2012)*. The mobile pyrolysis units feedstock input rate was 40 tons/day (80,000 lbs/day) and utilized 40.0 ac/day. The area of switchgrass required to supply a mobile pyrolysis unit for one year was 14,611 acres (40.0 ac/day x 365 days).

Model builder

ArcGIS Model Builder was used to automate the GIS procedures to analyze the logistics for mobile pyrolysis units. Model builder automates individual procedures by using model tools and scripts. Figure 2.3 shows a flowchart of the Model Builder procedures used to determine feedstock availability for mobile pyrolysis units. These procedures included, (1) grid files and crop field shape files were merged, (2) the merged files were dissolved for each grid cell, and (3) planted area and biomass production within each grid cell were calculated. Figure 2.4 shows a flowchart of the Model Builder procedure used to generate the route and calculate the distance between two mobile pyrolysis stations and the distance to the closest oil refinery. The procedures included, (1) the planted areas within each grid cell were used to find the centroid location using the zonal geometry function, (2) the centroid locations in raster format were converted to point files, (3) road network data was imported to Network Analysis, (4) centroid points were transferred to Network Analysis, and (5) the shortest route was calculated.

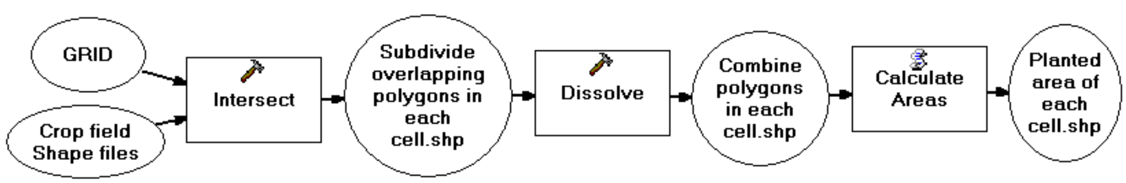


Figure 2. 3 A flowchart of the Model Builder procedure used to determine feedstock availability for mobile pyrolysis units in the NC region.

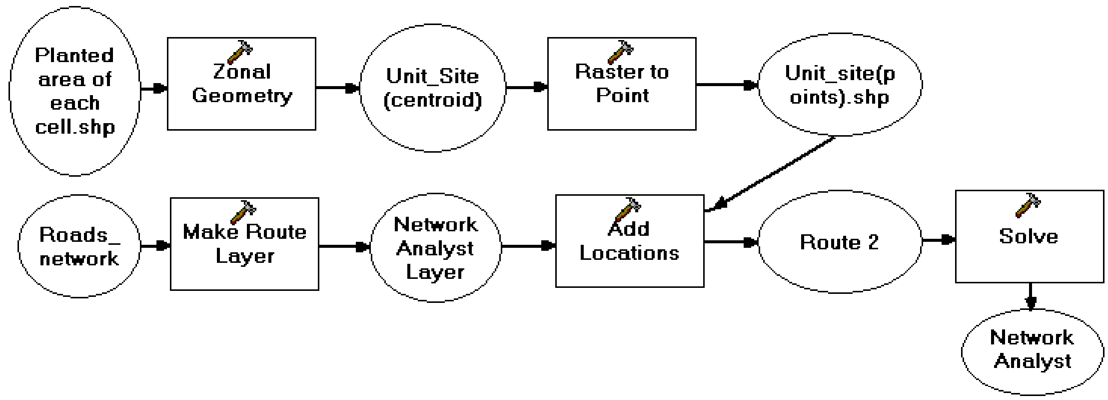


Figure 2. 4 A flowchart of the Model Builder procedure used to route, 1) mobile pyrolysis units from one station to next station, and 2) distances from the mobile pyrolysis station to the closet oil refinery.

Network analysis

Flexibility and simplified feedstock logistics are a major strength of the mobile pyrolysis concept to produce bio-crude oil. A basic assumption was that the mobile pyrolysis units were located in the center of each grid cell. Therefore the average distance for feedstock to move to a mobile pyrolysis unit was assumed to be half the grid cell dimension. It was also assumed that the average distance required to transport biochar back to the feedstock production fields was half the grid cell size. The Network Analysis extension of ArcGIS was used to calculate, (1) distances from one mobile unit station to the next station, and (2) distances to the nearest oil refinery. Model Builder was used to simplify and automate these processes. Figure 2.4 shows the flowchart of the Model Builder procedure used to generate the route (from one mobile pyrolysis station to the next station) based on planted area and yields of each cell and road networks. The feedstock areas were polygon files that were used to determine the center point in each grid cell using the zonal geometry function in Spatial Analysis. The raster center area was then converted to a point. These points were added to Network Analysis to calculate the routes using the shortest distance option. The routing layer (lines) was developed to find the optimal route between pyrolysis sites (points) or to the closest refineries (points).

Linkage to the economic model

The GIS analysis focused on creating an automated process that integrated the feedstock logistics model with a stochastic economic model *(Richardson, Schumann, and Feldman 2008)*. The GIS analysis model determined the optimum locations for the mobile pyrolysis stations and the move distance to each harvest area, as well as distances to the nearest oil refineries. The economic model uses a Monte Carlo simulation model and a sensitivity analysis to determine the cost per barrel to produce bio-oil to assess alternative oil prices and feedstock costs scenarios. This economic simulation model was programmed in Excel using the add-in function SIMETAR for simulation and risk analysis. The economic model used cumulative distribution functions (CDF). Different scenarios were combined with a Monte Carlo financial simulation model and were used to analyze the probability of economic capability of a pyrolysis system for alternative feedstocks, locations, and frequency of mobile pyrolysis movements.

Software

ESRI ArcMap 9.3 version and ArcGIS Desktop 9.3 Service pack 1 were used for the GIS analyses. This software was run on a Dell precision T7500 workstation with

Quad Core Intel R Xeon R Processor E5504 2.0GHz, 4M L3, 4.8GT/s. The memory is 4GB and the graphic card is 1.0GB to support high resolution images in ArcGIS.

Results

The GIS program utilizes a combination of automatic and manual procedures. Model builder run times varied based on the pyrolysis move times (1 to 12 months) which in turn affected grid sizes. For the entire NC region, the run times for creating grids varied from 30 minutes (grid size of 10,000 m) to 3 days (grid size of 1,000 m).

Grid sizes

Square grids, based on the area required to supply feedstocks to a mobile pyrolysis unit for 1, 2, 4, 6, 8, 10 and 12 month move times, were developed for the NC region (Table 2.1). These grids were placed over the themes with the corn and sorghum production fields.

Table 2.1 The square grid sizes based on mobile pyrolysis unit move times (1 to 12 months) for corn stover and energy sorghum feedstocks that were used in the GIS analyses.

Move Time		Grid Size (m)	
(month)	Corn Stover	Energy Sorghum	Switchgrass
1	2,400	5,000	3,300
2	3,500	8,100	5,000
4	4,500	12,000	7,000
6	6,200	15,000	8,500
8	7,300	19,000	9,800
10	8,100	22,000	11,000
12	9,600	23,000	12,000

The grid size for corn stover was found to range from 2,400 to 9,600 m and the grid size for energy sorghum from 5,000 to 23,000 m. The grid size for swtichgrass ranged from 3,300 to 12,000 m. The grid size was based on the area required to supply feedstock to a mobile pyrolysis unit based on move times of one month to twelve months.

Routing the mobile pyrolysis units

Next, model builder calculated the shortest distance routes using Network Analysis in ArcGIS for, (1) moving the mobile pyrolysis unit from one station to the next station, and 2) moving the bio-oil to the closest oil refinery. Figure 2.5 shows nodes (points) and links (lines) in Network Analysis, which were obtained from road and street line files in the U.S. Census Bureau ftp server. Two main objects in the Network

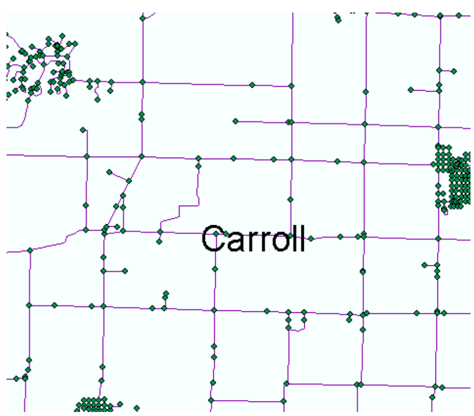


Figure 2. 5 ArcGIS Network Analysis used road network data to create links and nodes in Carroll County, IL. There links and nodes were used to calculate the shortest route between mobile pyrolysis stations and the shortest route from the pyrolysis station to the nearest oil refinery.

Analysis are the node and the link. Links show the relationships between nodes. A link always connects two junctions.

In Network Analysis, run times for selecting study locations and calculating transportation routes were relatively short(less than 5 minutes). Figure 2.6 shows the optimum routes calculated by Network Analysis to move a mobile pyrolysis unit between corn stover feedstock locations 10, 11 and 12 for a 1 month move time in Carroll County, IL. The routing method was based on finding the shortest distances between pyrolysis stations.

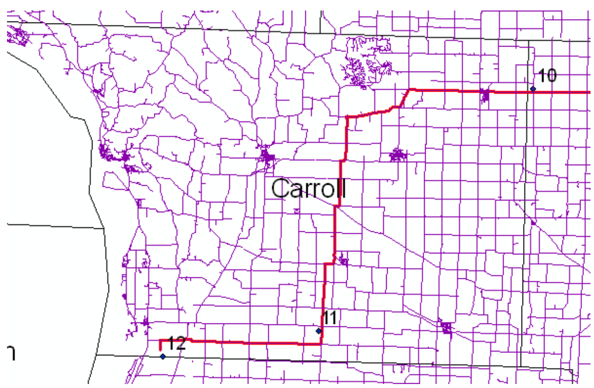


Figure 2. 6 An example of the output from Network Analysis for routing a mobile pyrolysis unit between pyrolysis stations 10, 11, and 12 for corn stover feedstock with a one month move time in Carroll County, IL.

Bio-oil to oil refinery

The optimum route to transport bio-oil from each mobile pyrolysis site to the closest oil refinery was determined using ArcGIS Network Analysis. Figure 2.7 shows the routing of bio-oil from pyrolysis stations in Nebraska to the closest oil refinery.

These pyrolysis stations are the optimum locations for the energy sorghum feedstock in the NC region. The shortest routing distance option was selected.

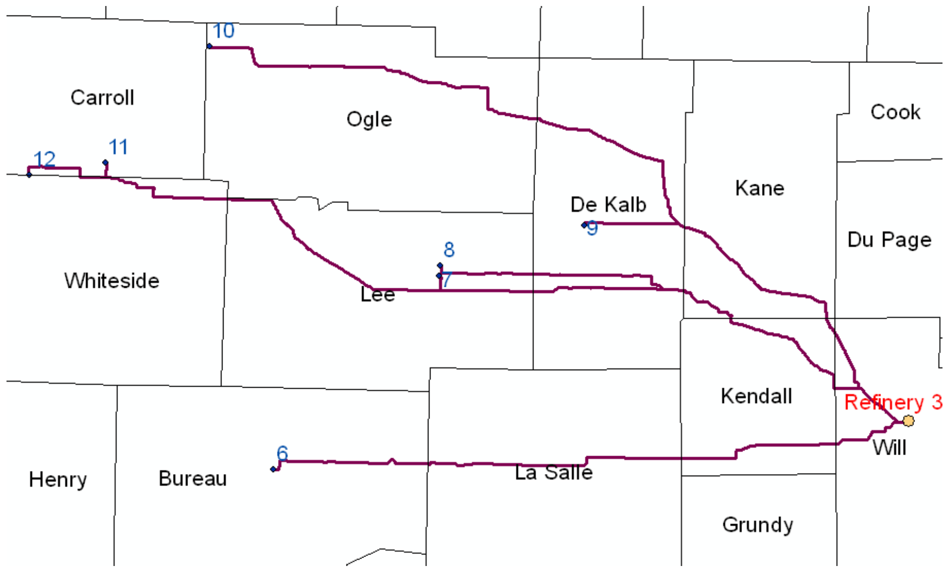


Figure 2. 7 An example of Network Analysis results for routing bio-oil from mobile pyrolysis stations (6 to 12) to the closest oil refinery (refinery 3) for energy sorghum feedstock in Nebraska.

Conclusions

A GIS program was developed to optimize the use of mobile pyrolysis units in the NC U.S. to produce bio-oil from agricultural feedstocks. A semi-automated GIS program was developed to determine the optimum locations, based on feedstock availability, for mobile pyrolysis units to produce bioenergy in the NC region. The shortest distances between mobile pyrolysis stations and the optimum route from the pyrolysis station to the nearest oil refinery was also determined. The feedstocks evaluated were corn stover, energy sorghum, and switchgrass. The cropland data layer (CDL) database from NASS provided the locations of feedstock production in the NC region. Since mobile pyrolysis units were moved to feedstock production fields, feedstock and biochar transportation distances were determined based on the size of the harvest grid size. Harvest grid sizes varied based upon scheduled mobile pyrolysis move times. Model Builder was used to automate the GIS procedures. First, Model Builder determined the optimum grid cell locations based on feedstock availability. The top biomass production cells were manually selected for mobile pyrolysis sites. The number of pyrolysis sites depended on the move time interval (1 to 12 months). Once, biomass production locations were selected for specific time periods, Model Builder identified two routes, (1) from one mobile pyrolysis station to the next station, and (2) from the mobile pyrolysis station to the closest oil refinery. The final output table from the GIS analysis included the grid size, feedstock and biochar transport distances from feedstock production fields to the mobile pyrolysis units, short distances from one mobile pyrolysis station to the next station, and distances from each mobile pyrolysis station to the closest oil refinery. This table was then imported into the economic model. This GIS program is flexible and can be applied to other regions and to other agricultural feedstocks as well. In future work the movement of mobile pyrolysis units will be integrated with weather prediction models. This will allow weather information and crop production forecasts to be factored into the management process to identify optimum locations for the mobile pyrolysis units.

CHAPTER III

OPTIMIZED FEEDSTOCK LOGISTICS FOR MOBILE PYROLYSIS UNITS IN NORTH CENTRAL REGION OF THE U.S.

Synopsis

Mobile pyrolysis units have the potential to greatly simplify feedstock logistics by moving pyrolysis equipment to the feedstock production fields. The concept is to use mobile pyrolysis units to convert low density biomass to high density bio-oil to minimize feedstock transportation costs. A recently developed GIS program was used to assess feedstock availability for mobile pyrolysis units in the North Central (NC) region using National Agricultural Statistics Service (NASS) using GIS databases. The feedstocks chosen for this study were corn stover, energy sorghum, and switchgrass. The GIS program identifies optimum locations for mobile pyrolysis stations based on feedstock availability and calculates the routes and distances between the optimum pyrolysis stations. The GIS program utilized a harvest grid concept with the mobile pyrolysis unit located in the center of the grid cell. It was assumed that the mobile pyrolysis units would move on discrete time steps of 1, 2, 4, 6, 8, 10 and 12 months (stationary). The harvest grid sizes ranged from 2.4 to 9.6 km for corn stover, from 5 to 23 km for energy sorghum, and 3.3 to 12 km for switchgrass, depending on move times. In the NC region, distances to move the mobile pyrolysis unit from one location to the next location varied from 2 to 139 km for corn stover, from 4.4 to 45.3 km for energy sorghum, and 3.0 to 21.5 km for switchgrass. Distances to transport the bio-oil to the

closest oil refineries ranged from 81 to 194 km for corn stover, 365 to 461 km for energy sorghum, and 192 to 227 km for switchgrass. The GIS program was coupled with the economic model (SIMETAR) to calculate the total cost of producing and transporting the bio-oil to an oil refinery. The highest probability of success was a stationary model (the mobile pyrolysis unit stayed one location for 12 months). However, mobile pyrolysis units had more flexibility under constraints.

Introduction

Renewable energy is an important concern due to globalization and increasing competition for natural resources. The North Central (NC) region is a primary source of corn production in the U.S. The corn stover that remains after the corn grain is harvested is a potential feedstock for mobile pyrolysis units. However, robust and efficient pyrolyzers are needed to produce effective emissions control systems, bio-oil refineries, and agricultural equipment for handling and incorporating biochar back to feedstock production fields *(Laird, 2008)*. The carbonized organic matter (biochar) that is produced during pyrolysis can have different basic physical and chemical properties depending on the pyrolysis technology used. Pyrolysis technology commonly used are, torrefaction (a pyrolysis process at low temperatures), slow pyrolysis, intermediate pyrolysis, fast pyrolysis, gasification, hydrothermal carbonization, or flash carbonization *(Meyer et al., 2011)*. Agricultural residues, such as corn stover, are obvious sources of biomass for pyrolysis. However, care must be taken to ensure that enough residue is left in the field for sustainable production avoiding impairment of land productivity, degradation water quality, or redundant carbon emissions *(Graham et al., 2007)*. A GIS program developed for the NC region calculated pyrolysis unit move distances, distance to refinery, available feedstock area and available feedstock biomass based on corn stover, energy sorghum, and switchgrass. The Conservation Reserve Program (CRP) protects millions of acres of American topsoil from erosion and is designed to safeguard the Nations' natural resources *(USDA, 2011)*. Some of CRP land may be a good source for a switchgrass feedstock to be grown in the future.

Study area

The feedstock logistics study focused on Illinois for corn stover, Nebraska for energy sorghum, and Nebraska for switchgrass (see Figure 3.1), because of their high production rates. Locations where corn was planted and harvested for grain as well as grain yields and production rates were obtained from NASS.

The feedstocks used in this study were corn stover, energy sorghum and switchgrass. Corn stover has high production rates throughout the NC region. The ratio between corn for grain and corn stover was assumed to be one to one *(Pordesimo et. al, 2004)*. It is assumed 25% of the corn stover was harvested and 75% of the corn stover remained as residue cover for erosion control and soil improvement. Energy sorghum was also studied as a feedstock due to high biomass production levels. It was assumed that energy sorghum would be planted NC region where grain sorghum is now planted. It was projected that 100% of energy sorghum would be harvested the energy sorghum yield was assumed to be 15 Mg/ha (13,399 lbs/ac) *(Heggenstaller et al., 2008)*. Mean

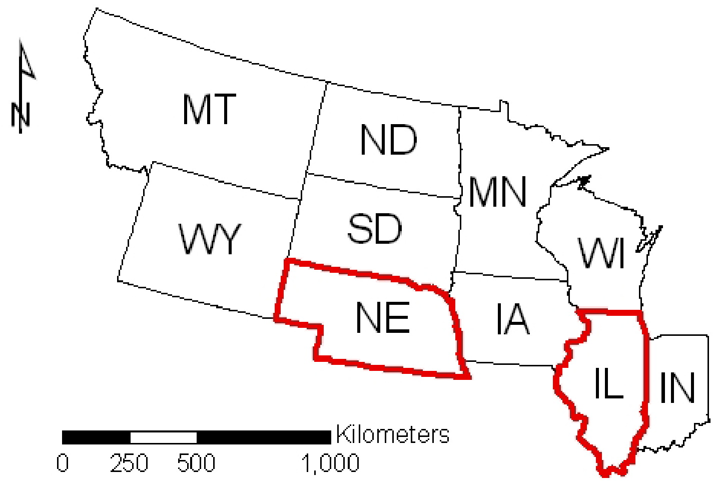


Figure 3. 1 The states in the North Central region that were included in this feedstock logistic study using mobile pyrolysis units. Feedstock logistics were evaluated in Illinois for corn stover, in Nebraska for energy sorghum, and in Nebraska for switchgrass.

annual switch grass yields were 6.3 Mg/ha for Nebraska, South Dakota, and North Dakota *(Kiniry et al., 2008).*

Pyrolysis

Pyrolysis is a method to thermally convert feedstocks to bio-oil, synthesis gas (syngas) and biochar. Slow pyrolysis generates biochar and pyrolysis gas with the advantage of high yields of biochar but the disadvantage of producing a relatively low-value syngas. In contrast, fast pyrolysis produces a sustainably higher value energy production, but it has high capital investment *(Brown et al., 2011)*. Pyrolysis units can be used to generate bio-oil and the syngas can be used to power generators to produce electricity. The fast pyrolysis units with generating systems have a huge potential to generate electricity at a profit in the long run, and at a lower cost than any other biomass to electricity system at a small scale *(Bridgwater et al., 2002)*. Plus, the bio-oil has the potential to be upgraded to transportation fuels at oil refineries. In addition, the biochar byproduct (30% of the input feedstock) contains nutrients that can be applied to the soil. Therefore, pyrolysis systems have the potential to convert diverse classes of feedstocks to bio-crude oil and syngas with the biochar being land applied to feedstock production fields in the NC region.

Most conventional biofuel systems utilize a centralized production facility that require large quantities of feedstocks. Large-scale plants may be economical in some regions, but there are many constraints such as weather, availability of feedstocks, and feedstock transportation logistics that must be considered. Large, centralized biomass processing plants can process up to 23,000 tonnes of biomass per day, but must contend with high expenses associated with transportation infrastructure, biomass storage and handling problems *(Wright et al., 2008)*. In addition, there are the same transportation and handling costs associated with returning the biochar back to the feedstock production fields *(Wright et al., 2008)*. *Roberts et al. (2010)* conducted a life cycle assessment to estimate the energy, climate change impacts, and the economics of biochar systems. The costs to transport feedstocks long distances are a significant obstacle to the economic profitability of pyrolysis and bio-char systems *(Roberts et al., 2010)*.

Mobile pyrolysis

Mobile pyrolysis units can be deployed close to feedstock sources to minimize feedstock transportation costs. For this project it was assumed that a mobile, 305 mm (1 foot) diameter pilot-scale fluidized bed pyrolysis system, was used to convert agricultural feedstocks to bio-oil, syngas, and biochar. The mobile pyrolysis unit processes feedstocks at a rate of 40 tons per day when the feedstock is at 10% or less moisture content. The system can produce bio-oil at a rate of 50 gallons per ton of feedstock and a biochar production rate of 10 tons per day *(S. Capareda, personal communication, 2009).* A typical mobile pyrolysis station requiring an area of 0.75 ac is shown in Figure 3.2. The mobile pyrolysis station would be located at the center of a harvest grid cell. In this system, agricultural feedstocks would be transported by local producers relatively short distances (0.8 – 5.0 km) to the mobile pyrolysis unit. The feedstocks would be dried, ground, and then pyrolyzed near the feedstock production fields. The pyrolysis units would be trailer mounted for easy transport and require approximately ¾ of an acre of land for set up (shown in Figure 3.3). Bio-oil would be stored in trailer tankers until a full load was produced and then full trailer tanks would be transported to the nearest existing oil refinery. Syngas produced by the mobile pyrolyizer would be used to generate electricity to power the pyrolysis station with the excess sold to the local electric utility and put on the electric grid. The biochar would be stored on site until a full load was obtained and then transported back to the agricultural production fields for land application as a soil amendment.

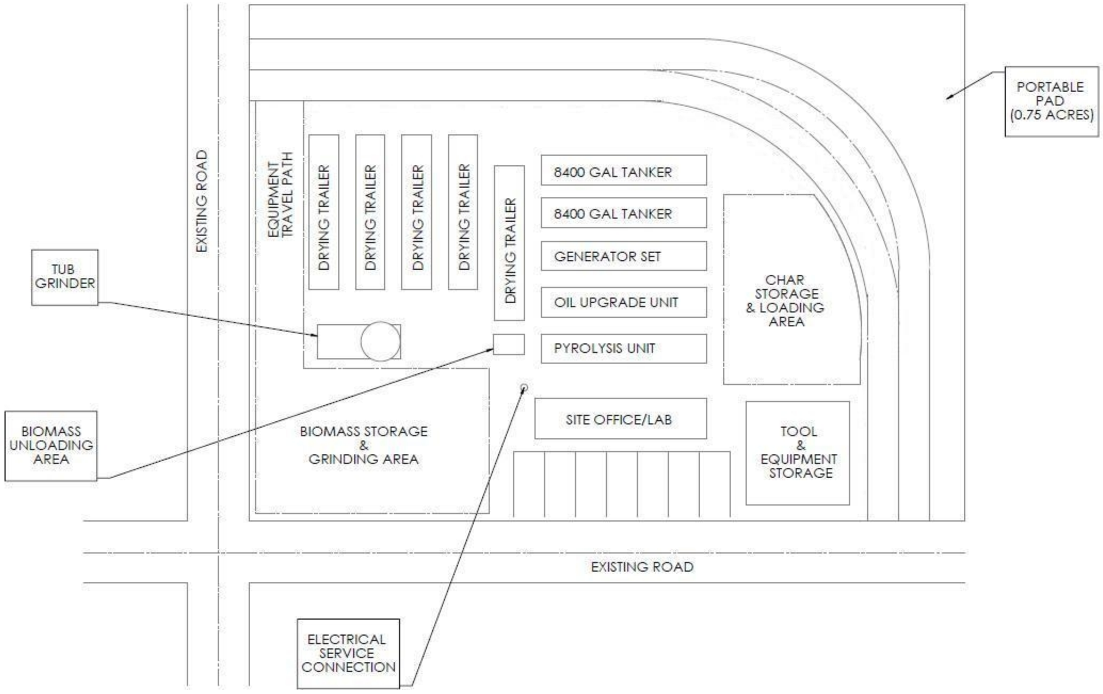


Figure 3. 2 The layout of a typical mobile pyrolysis station that could be used to convert biomass to bio-oil near feedstock production fields.

Figure 3. 3 The pyrolysis units would be trailer mounted with about ¾ of an acre of land for set up.

After all of the feedstock in the grid cell has been harvested, the mobile pyrolysis unit would be moved to the next harvest grid and another pyrolysis station established. Distributed biomass processing has the potential of reducing biomass delivery costs by densifying biomass before shipping to an oil refinery for upgrading to renewable transportation fuels *(Wright et al., 2008).*

In this paper, a GIS program previously developed (Chapter II) was used to identify optimum locations for mobile pyrolysis stations in the NC region. The feedstocks evaluated were corn stover, energy sorghum, and switchgrass. The GIS analyses determined feedstock hauling distances and optimum routes between mobile pyrolysis stations as well as distances required to haul bio-oil to the nearest oil refinery. The GIS results were coupled with an economic model that used SIMETAR. SIMETAR is a simulation and risk analysis software package that uses the Monte Carlo statistical analysis model *(Richardson, Schumann, and Feldman 2008)* to analyze the economic feasibility of a mobile pyrolysis system.

Literature Review

There are many different kinds of feedstock that can be used in pyrolysis systems to produce bio-oil. Biomass energy can be produced from agricultural residues, forest products, municipal solid waste (MSW), animal waste and poultry manure. The theoretical energy potential from recoverable biomass resources was evaluated in Bangladesh *(Mondal and Denich, 2010)*. In this study, the total biomass production was estimated and the energy potential was calculated by applying the individual energy recovery rate, the residue to yield ratio (for agricultural residues only), moisture content and calorific value *(Mondal and Denich, 2010)*.

The availability of corn stover residue in an area depends on both field-level and landscape-level resources as well as logistical factors that affect delivered costs. Economic offsets for scale must also be factored into the viability of the conversion process *(Perlack and Turhollow, 2003)*. Transportation, collection and baling, and farmer payments are responsible for over 90% of total delivered cost, and the cost difference between facility sizes is as a direct result of transportation. Various agricultural crops can be used for pyrolysis such as corn stover, sorghum, switchgrass, rich, wheat, sugar cane, straw and miscanthus *(Mohan et al., 2006)*. The development of a sustainable feedstock supply and its cost depend on the choice of feedstock and the logistics available for management. The U.S. Department of Energy is currently evaluating alternative harvesting, handling, transport logistics and densification technologies to use agricultural residues for bioenergy.

One of the byproducts of the pyrolysis system is biochar which has a potential advantage as a soil amendment. Biochar application to soils is hypothesized to increase water holding capacity, build soil organic matter, improve nutrient cycling, lower bulk density, and reduce leaching of pesticides and nutrients to surface and ground water *(Laird, 2008)*. *McCarl (2009)* conducted an economic analysis which is a combination of energy product yields, biochar as a soil additive, greenhouse gas (GHG) offsets and other chemical products. *McCarl (2009)* found fast and slow pyrolysis to be currently unprofitable because of sensitivity of crop yield enhancement, plant fixed/operating costs, and GHG and energy prices. Removing biomass residues from agricultural fields may increase soil erosion rates. *Newman et al. (2010)* studied hypothetical management scenarios at 17,848 National Resources Inventory (NRI) data points throughout Iowa using the Water Erosion Prediction Project (WEPP) *(Flanagan et al. 2007)* to estimate average annual soil loss. Their study focused on simulated impacts of corn stover removal on soil erosion and the results included computer simulations of soil erosion by water under different corn stover harvesting and management scenarios, applied universally across Iowa. Corn stover harvest affected soil erosion by water and is one of the potentially limiting factors for determining a sustainable rate of corn stover. The study concluded that soil productivity and water quality could be negatively affected by poor residue management practices *(Newman et al., 2010)*. In addition, harvesting corn stover may decrease soil organic carbon levels and soil nitrogen contents, and increase soil erosion *(Mann et al., 2002)*. Corn stover removal for renewable biofuel production would decrease net non-renewable fuel consumption, while increasing the threat of contamination of water quality due to soil erosion *(Kim and Dale 2005)*.

The grid concept has been used in previous studies for the optimal use of agricultural and forest residue for bioenergy production based on biomass availability *(Biberacher and Gadocha, 2009; Miehle et al., 2006; Perpina et al., 2009; Velazquez-Marti and Annevelink, 2009)*. A GIS-based spatial distribution of biomass resources with an optimization model was developed to locate bio-refineries near agricultural, forest, urban and energy crop biomass sources across the Western United States *(Parker et al., 2010)*.

Materials and Methods

Feedstocks

Corn stover, energy sorghum and switchgrass were selected as feedstocks for this study. Corn has high production rates in the NC region. The following equation was used to estimate the total corn stover biomass (lb) for pyrolysis.

Corn stover biomass = 10 year average corn yield (bu/ac) x 56 (lbs/bu) x 0.25 x area (ac)

Eq. 3.1

The ratio of corn for grain (kg) and corn stover (kg) was assumed to be one to one and one bushel of corn was assumed to be 25.4 kg (56 lbs) *(USDA, 2010b)*. It was assumed that only 25% of the corn stover would be available for the mobile pyrolysis units. The rest (75%) of the corn stover will be left in the field for erosion prevention and soil improvement. The energy sorghum was chosen for analysis because it has high biomass production rates for biofuels. Energy sorghum was assumed to yield approximately 5.60 Mg/ha with 100% available for harvest *(Baltensperger, 2012)*. It was assumed that energy sorghum would be planted in fields where grain sorghum is now grown. There is very little switchgrass now grown in the U.S., but, CRP lands might be a good source for switchgrass in the future. Mean annual switchgrass yields were 2.24 Mg/ha for northern Nebraska *(Baltensperger, 2012)*.

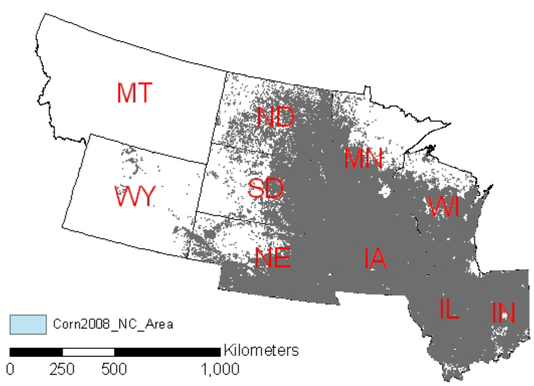
GIS software / hardware requirements

ESRI ArcMap 9.3.1 version and ArcGIS desktop 9.3. service pack 2 were used for the GIS analyses and the spatial analyst and the network analyst were used as an extension. This software was run on a Dell Precision T7500 workstation with Quad Core Intel R Xeon R Processor E5504 2.0GHz, 4M L3, 4.8GT/s with 4GB of memory and a 1.0 GB graphic card to support high resolution images in ArcGIS. GIS programs were developed to optimize the movement of mobile pyrolysis units to minimize feedstock transportation costs for the NC region (Chapter II). The Network Analysis extension of ArcGIS was used to calculate distances from one mobile pyrolysis station to the next station, and distances from the pyrolysis station to the closest oil refinery.

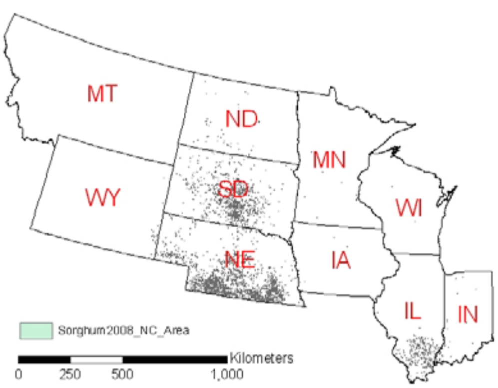
GIS program procedures

Mobile pyrolysis units were assumed to be located at the center of the harvest grid and therefore, feedstock travel distances were assumed to be one half the grid size. In addition, hauling distances to deliver biochar back to feedstock production field was also assumed to be one half the harvest grid size. The GIS analysis determined harvest grid sizes for mobile pyrolysis unit for move times of 1, 2, 4, 6, 8, 10, and 12 months. The move times and grid sizes are related; the longer the mobile pyrolysis unit stayed in one location the bigger the grid size. Optimum routes to move the mobile units from one pyrolysis station to the next station were determined using Network Analysis.. Network Analysis was also used to determine the route distance from each mobile pyrolysis unit to the closest oil refinery. Model Builder was used to automate the GIS procedures used to conduct the logistics for the mobile pyrolysis units. The locations of actual planted corn and sorghum areas for the NC region were obtained from the 2008 crop data layer (CDL) *(USDA, 2010a)* database from the spatial analysis research section of National

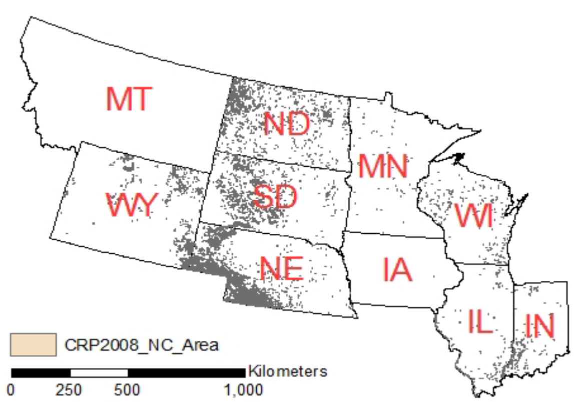
Agricultural Statistics Service (NASS). There were image files with a resolution of 56 m. Figure 3.4 shows the locations of corn (planted in 2008), sorghum (2008), and CRP (2010) areas in the NC region. The location of CRP land in the NC region was obtained from the CDL data *(USDA, 2010a).*



Corn fields



Sorghum fields



CRP lands

Figure 3. 4 Location of corn and sorghum fields in the North Central States in 2008 (USDA, 2010b).

Harvest grid sizes were determined using ArcObject based on corn stover production rates (county basis), the mobile pyrolysis consumption rate (40 tons/day), and mobile pyrolysis move times (1 to 12 months). Square harvest grids varied from 2.4 km (1 month) to 9.6 km (12 months) for corn stover, from 5.0 km (1 month) to 23.0 km (12 months) for energy sorghum, and from 3.3 km (1 month) to 12.0 km (12 months) for switchgrass. Therefore, the one month move time for the mobile pyrolysis unit had twelve locations each year and the six month move time had two locations each year. Various grid sizes were coded in ArcObject (a macro function of ArcGIS) and run times for creating grids for the NC region varied from 2 minutes for the largest grid size (23.0 km) to 1 day for the smallest grid size (2.4 km). The GIS analysis identified optimum locations for mobile pyrolysis stations based on biomass harvest rates using historic crop yields (10 year average from NASS *(USDA, 2010b)*). The GIS program with Model Builder required from 5 minutes and 4 hours to calculate available biomass and to show mobile pyrolysis unit routes and distances to the nearest oil refineries, depending on the grid size.

Results

The grid sizes were decided based on the area required to supply feedstocks to a mobile pyrolysis unit for each time interval. From the pilot study, the top 100 locations for corn stover were located in Illinois (57 sites), Nebraska (29 sites), and Iowa (14 sites). The highest corn stover feedstock location was in Hall County, NE. The average corn production rates range from 156 bu/ac to 176 bu/ac for the top 100 harvest grids (the grid size 6.2 km) in the NC region. Energy sorghum was assumed to replace grain sorghum in the NC region. For energy sorghum, the top 50 locations for grain sorghum production (the harvest grid size 20.0 km) were located in Nebraska (35 sites) and South Dakota (15 sites). The highest sorghum feedstock production grid was in Thayer County, NE. The simulation focused on transporting one mobile pyrolysis unit over the year for different hauling time intervals (1, 2, 4, 6, 8, 10, and 12 months). Hauling distances to transport 1) from feedstock fields to each mobile pyrolysis station, 2) from the mobile pyrolysis station to next pyrolysis station, and 3) from the mobile pyrolysis station to the closest refinery were calculated using developed GIS programs (Chapter II). The study areas for corn stover and energy sorghum were decided based on the pilot study; mobile pyrolysis transported in IL for corn stover and in NE for energy sorghum and switchgrass fields. The biomass production rate of sorghum was assumed to be 5.60 Mg/ha *(Baltensperger, 2012)*. For switchgrass, mobile pyrolysis moved and produced bio-oil in NE where the mean annual switchgrass yields of 2.24 Mg/ha was obtained by *Baltensperger (2012)*. Table 3.1 shows feedstock hauling distances to transport from feedstock fields to each mobile pyrolysis station for different move time intervals (1, 2, 4, 6, 8, 10, and 12 months).

Table 3. 1 Feedstock hauling distances to transport from the fields to a mobile pyrolysis station for three feedstocks.

Move Time	Feedstock hauling distances (km)		
(month)	Corn Stover	Energy Sorghum	Switchgrass
1	1.2	2.5	1.65
2	1.75	4.05	2.5
4	2.25	6.0	3.5
6	3.1	7.5	4.25
8	3.65	9.5	4.9
10	4.05	11.0	5.5
12	4.8	11.5	6.0

Mobile pyrolysis unit routings for corn stover

For a mobile pyrolysis unit with a one month move time, the top 12 corn stover feedstock production fields were located in Carroll, Ogle, Lee, De Kalb, Bureau, Tazewell, Sangamon, and Christian Counties in Illinois (see Figure 3.5). The number one corn stover feedstock production grid was located in Lee County, Illinois. In Illinois, corn stover feedstock hauling distances varied from 2.4 km for a 1 month move time 9.6 km for a 12 month move time. Figure 3.5 and Table 3.2 shows the optimized routing of a mobile pyrolysis unit to the top 12 corn stover feedstock sites in Illinois. Pyrolysis unit move distances from one location to the next location varied from 2 to 139 km with an average distance of 48 km. For a two month move time, pyrolysis unit move distances varied from 9 to 139 km. For a 4 month move time, pyrolysis unit move distances varied from 8 to 55 km. For 6, 8, and 10 months move times, pyrolysis unit move distances were 79, 28, and 77 km, respectively. For a 12 month move time, the mobile pyrolysis unit would be located at the top one corn production location is located in Lee County, IL, with a harvest grid size of 2,400 m.

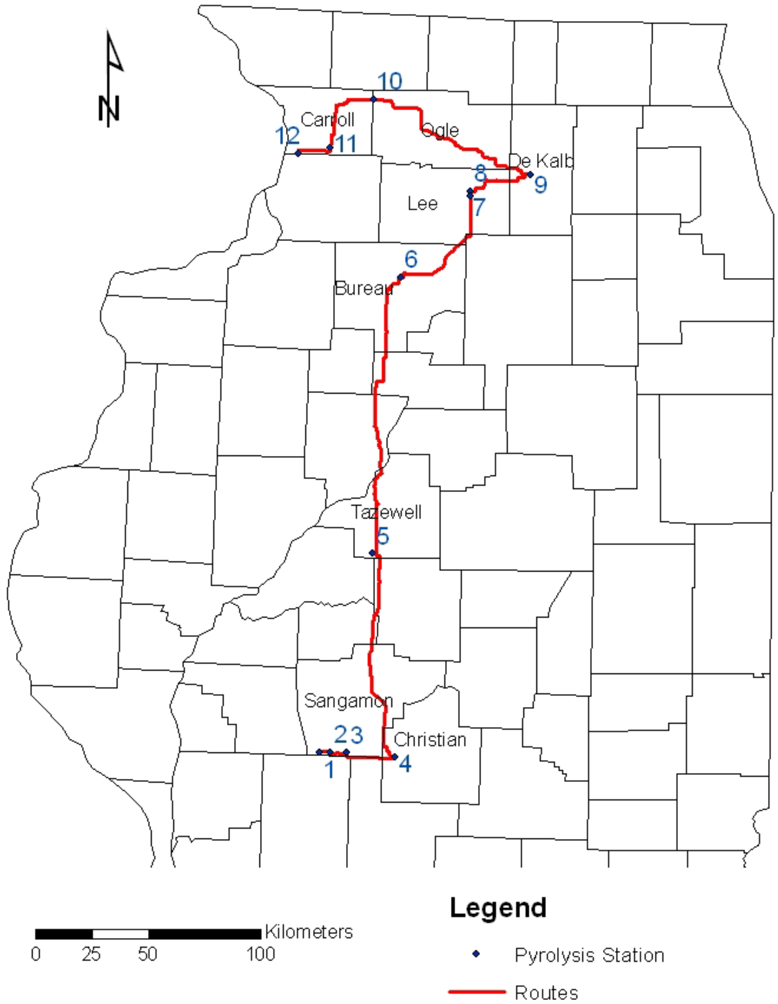


Figure 3. 5 The optimized route map for a mobile pyrolysis unit to move to the top 12 corn stover feedstock sites in Illinois. This analysis was based on a squre havest grid (2,400 m) and one month move times.

Table 3. 2 Each move distance and average distance of a mobie pyrolysis unit to move the top 12 corn stover feedstock sites in Illinois.

Station	Move distance (km)
1	0.0
2	6.2
3	8.6
4	24.3
5	106.7
6	138.7
7	59.2
8	2.1
9	34.3
10	95.9
11	39.2
12	16.85
Average	48.4

Bio-oil routing for corn stover

For a move time of 1 month, the distances from the mobile pyrolysis station to the closest oil refinery varied from 81 to 194 km. The oil refineries closest to the mobile pyrolysis stations in IL are located in Will County and Madison County *(USDOE, 2009)*. The average distance from the mobile pyrolysis sites to the closest refinery was 128 km. Figure 3.6 and shows the optimized route map from mobile pyrolysis stations to the nearest oil refinery for the top 12 corn production locations in Illinois. Table 3.3 shows the move distances from mobile pyrolysis stations to the closest oil refineries for 1, 2, 4, 6, 8, 10, and 12 month move times.

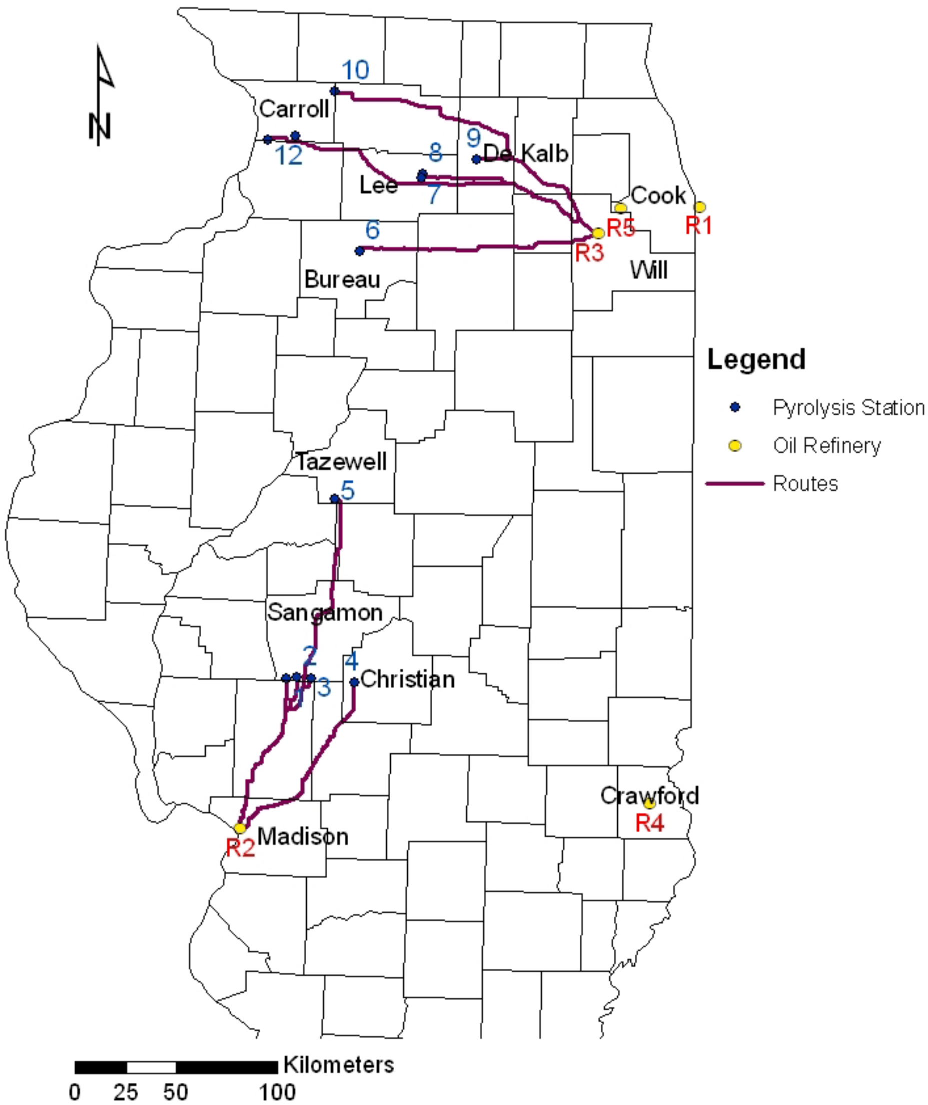


Figure 3. 6 The optimized route map to transport bio-oil from mobile pyroysis stations to oil refineries for the top 12 corn production sites in Illinois. This analysis was based on a squre harvest grid (2,400 m) and one month move times.

Table 3. 3 The distances required to transport bio-oil from the mobie pyrolysis stations to the closest oil refinery for the top 12 corn stover feedstock sites in Illinois.

Station	Distance to Refinery (km)
1	88.5
2	92.5
3	96.6
4	109.0
5	194.3
6	126.7
7	103.5
8	104.4
9	81.3
10	171.6
11	176.2
12	190.5
Average	127.9

Mobile pyrolysis unit routings for energy sorghum

The GIS program was used to establish optimum locations for mobile pyrolysis stations for energy sorghum for move times of 1, 2, 4, 6, 8, 10, and 12 months. For a mobile pyrolysis unit with a one month move time, the top 12 sorghum production fields were located in Furnas, Red Willow, Frontier, Hayes, Hitchcock, Dundy, and Chase in Nebraska (Figure 3.7). The number one location was located in Red Willow County in Nebraska for twelve month move time. Feedstock hauling distance for energy sorghum varied from 5.0 km for a 1 month move time to 23.0 km for a 12 month move time. Pyrolysis unit move distances from one location to the next location varied from 4.4 to 68.8 km with an average move distance of 31.7 km. Figure 3.7 and Table 3.4 shows the optimized route map for a mobile pyrolysis unit to the top 12 sorghum feedstock sites in NE.

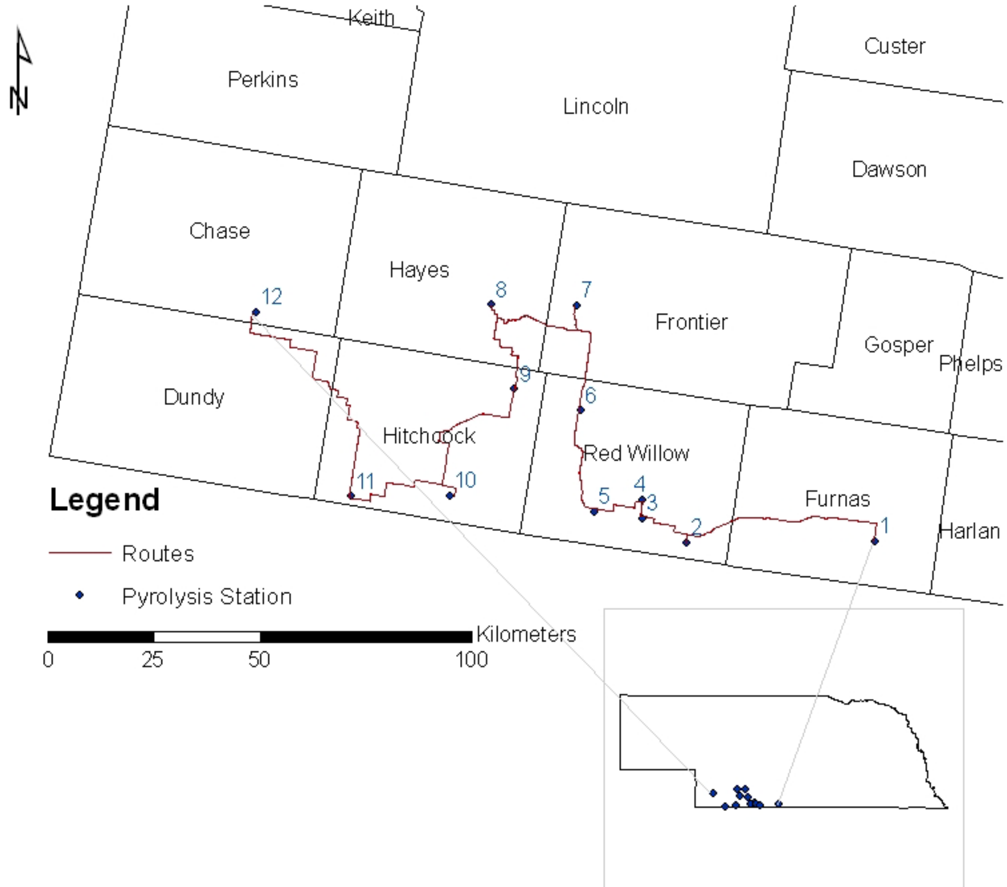


Figure 3. 7 The optimized route map from a mobile pyrolysis unit to move to the top 12 sorghum production sites in Nebraska. This analysis was based on a squre havest grid (5.0 km) and one month move times.

Table 3. 4 The move distances required for a mobie pyrolysis unit to move to the top 12 sorghum feedstock sites in Nebraska.

Station	Move Distance (km)
1	0
2	52.5
3	15.3
4	4.4
5	14.7
6	27.7
7	28.0
8	32.6
9	28.0
10	43.9
11	32.6
12	68.8
Average	31.7

Bio-oil routing for energy sorghum

Distances from the mobile pyrolysis station to the closest oil refinery varied from 365.3 to 521.7 km for one month move times. The closest refinery is located in Laramie County, WY *(USDOE, 2009)*. Figure 3.8 and Table 3.5 shows the optimized route map to transport bio-oil from mobile pyrolysis stations to the closest oil refinery for the top 12 sorghum production sites in Nebraska. The average distance from the pyrolysis sites to the closest oil refinery was 438.1 km.

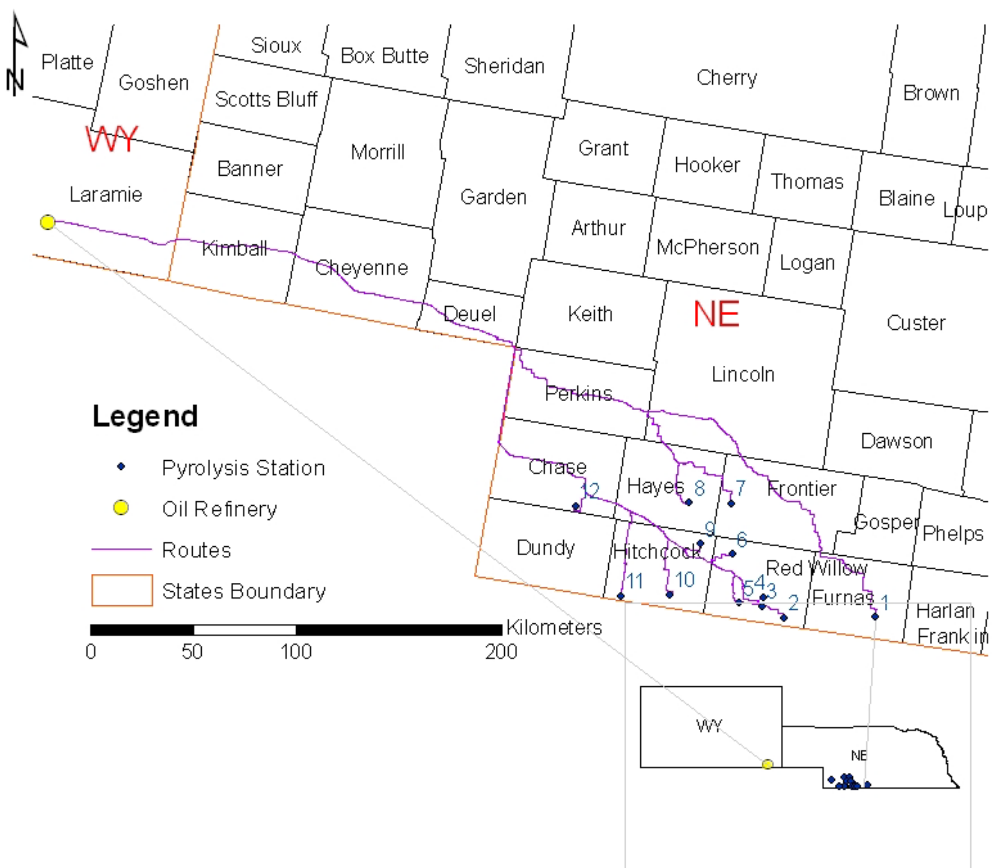


Figure 3. 8 The optimized route map from mobile pyrolysis stations to the nearest oil refinery for the top 12 sorghum production sites in Nebraska. This analysis was based on a squre harvest grid (5.0 km) and a one month move time.

Table 3. 5 The distances required to transport bio-oil from a mobie pyrolysis station to the closest oil refinery for the top 12 sorghum feedstock sites in Nebraska.

Station	Distance to Refinery (km)
1	521.7
2	477.9
3	462.6
4	462.9
5	451.7
6	437.0
7	415.6
8	394.6
9	418.5
10	430.3
11	418.7
12	365.3
Average	438.1

Mobile pyrolysis unit routings for switchgrass

Figure 3.9 and Table 3.6 show the optimum locations and the route for a mobile pyrolysis unit that uses switchgrass feedstock in Nebraska. The mobile pyrolysis unit would stay in each location for one month and pyrolyze all of the switchgrass in a square grid 3.3 x 3.3 km before moving to the next site. Distances from the mobile pyrolysis unit to the next location varied from 3.0 to 41.9 km for one month move times. Distances to the closest oil refinery ranged from 192.1 to 265.0 km.

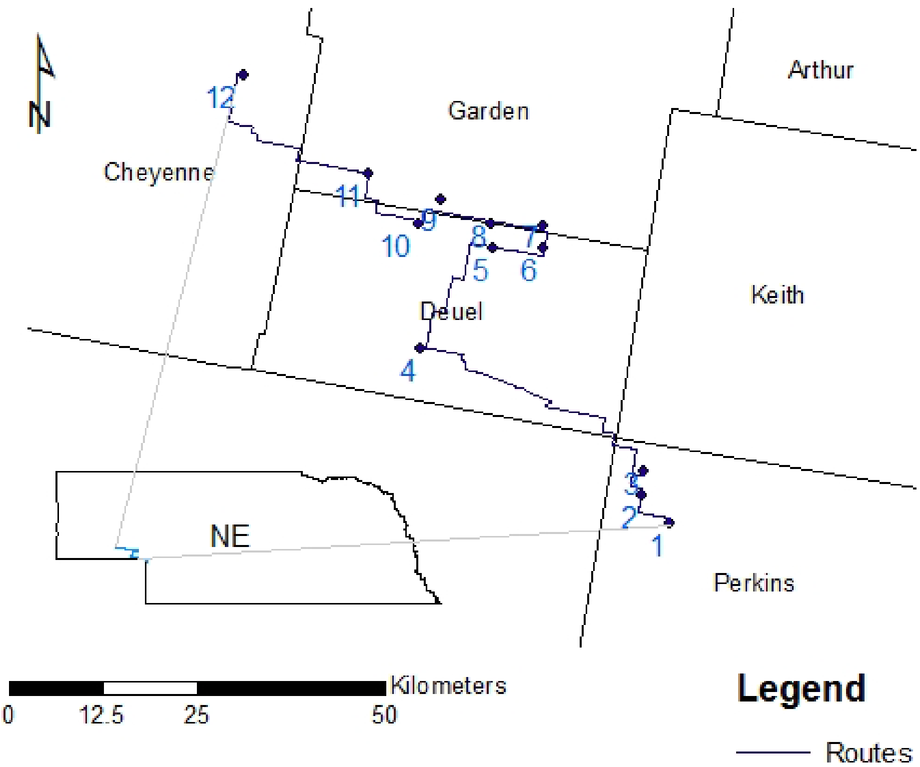


Figure 3. 9 The optimized route map from a mobile pyrolysis unit to move to the top 12 switchgrass production sites in Nebraska. This analysis was based on a squre havest grid (3.3 km) and one month move times.

Table 3. 6 The distance required to move a mobie pyrolysis unit to move the top 12 switchgrass feedstock sites in Nebraska.

Station	Move Distance (km)
1	0.0
2	6.5
3	5.8
4	41.9
5	21.8
6	7.7
7	3.0
8	6.9
9	7.0
10	4.1
11	12.3
12	30.3
Average	13.4

Bio-oil routing for switchgrass

Distances from the mobile pyrolysis station to the closest oil refinery (in Laramie County, WY) varied from 192 to 267 km for one month move times. Figure 3.10 and Table 3.7 shows the optimized route map to transport bio-oil from mobile pyrolysis stations to the closest oil refinery for the top 12 switchgrass production sites in Nebraska. The average distance from the pyrolysis sites to the closest oil refinery was 226 km.

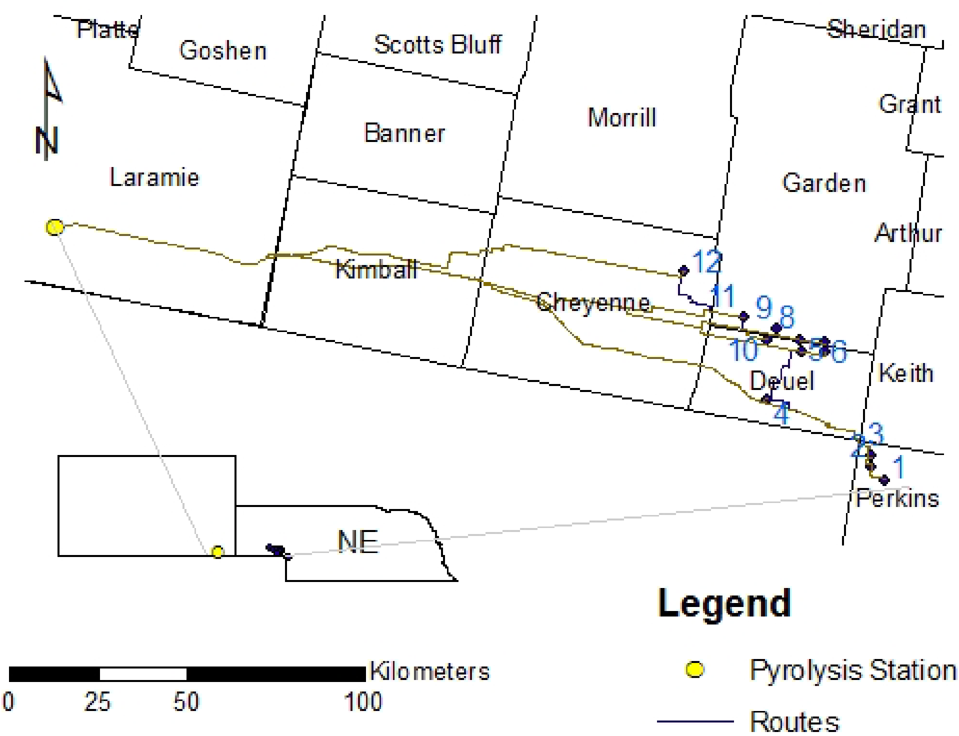


Figure 3. 10 The optimized route map to transort bio-oil from mobile pyrolysis stations to the nearest oil refinery in Laramie, WY, for the top 12 switchgrass production sites in Nebraska. This analysis was based on a squre harvest grid (3.3 km) and a one month move time.

Table 3. 7 The distances required to transport bio-oil from mobie pyrolysis stations to the closest oil refinery for the top 12 switchgrass feedstock sites in Nebraska.

Station	Distance to Refinery (km)
1	265.0
2	258.4
3	255.5
4	216.3
5	223.3
6	231.0
7	229.5
8	222.5
9	215.5
10	214.6
11	205.7
12	192.1
Average	227.5

Table 3.8 tabulated in the average, minimum, and maximum distances to transport from each mobile pyrolysis station to the next mobile pyrolysis station for different feedstocks in IL/NE with the different move time intervals (1, 2, 4, 6, 8, 10, and 12 month). Table 3.9 provides the average, minimum and maximum move distances required to transport bio-oil from the mobile pyrolysis station to the closest oil refinery for the corn stover, bioenery sorghum, and switchgrass feedstocks in the NC region. The mobile pyrolysis unit would stay in each location for 1, 2, 4, 6, 8, 10, and 12 month intervals and pyrolyze all of corn stover, energy sorghum, and switchgrass within the squre harvest grids.

Table 3. 8 The average, minimum, and maximum distances to transport from the mobile pyrolysis station to the next station for three feedstocks (corn stover, energy sorghum, and switchgrass) in IL or NE, based on one year scenarios (monthly, bi-monthly, quaterly, bi-annnual and stationary).

Feedstock	Corn stover (IL)			Energy sorghum (NE)			Switchgrass (NE)		
	Distance (km)			Distance (km)			Distance (km)		
Move time (mo.)	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min	Max.
1	48.4	2.1	138.7	31.7	4.4	68.6	13.4	3,0	41.9
2	60.8	8.5	139	27.6	5.6	45.3	17.2	4.8	38.4
4	31.5	8.2	54.7	33.4	13.1	53.6	19.8	18.1	21.5
6	78.6	-	-	18.3	-	-	16.1	-	-
8	27.9	-	-	57.9	-	-	60.7	-	-
10	77.4	-	-	81.0	-	-	22.6	-	-
12	Stationary			Stationary			Stationary		

Table 3. 9 The average, minimum and maximum distances to transport bio-oil from mobile pyrolysis stations to the closest refinery for three feedstocks (corn stover, energy sorghum, and switchgrass) in IL or NE.

Feedstock	Corn stover (IL)			Energy sorghum (NE)			Switchgrass (NE)		
	Distance (km)			Distance (km)			Distance (km)		
Move time (mo.)	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
1	128	81	194	438.1	365.3	521.7	227.5	192.1	265.0
2	137	105	195	437.2	393.1	475.0	217.0	195.2	235.2
4	111	102	125	443.6	416.2	461.1	218.5	203.3	234.1
6	139	102	177	470.4	461.6	479.2	222.4	217.8	227.0
8	93	84	102	439.5	412.0	467.0	242.9	224.6	261.1
10	143	107	178	440.0	405.5	474.5	227.2	221.5	232.9
12	102	-	-	474.3	-	-	218.5	-	-

The GIS feedstock logistics model was integrated with the SIMEATAR economic model to calculate revenue for converting agricultural feedstocks to bio-oil using mobile pyrolysis units in the NC region. Prices were calculated randomly from probability distributions estimated from historic series, therefore, income was calculated stochastically *(Palma et al., 2011)*. The output from the GIS feedstock program (feedstock hauling distances from the fields to a mobile pyrolysis station, optimal routes and distances from the mobile station to the next station, and optimal routes and distances of transporting the bio-oil to a refinery) was input to the financial simulation model that was optimized for transportation logistics costs.

Conclusion

A GIS program developed to assess feedstock logistics was used to determine the optimum locations for mobile pyrolysis units in the NC region based on feedstock availability. The feedstocks evaluated were corn stover, energy sorghum, and switchgrass. Feedstock logistics were evaluated for move times of 1 to 12 months for the mobile pyrolysis units. The GIS program determined the distances required to move, 1) feedstock from production fields to the mobile pyrolysis station, 2) the mobile pyrolysis unit from one pyrolysis station to the next station, and 3) bio-oil from the pyrolysis stations to the nearest oil refinery. Transporting switchgrass of three feedstocks covered the shortest distance to transport feedstock to the mobile pyrolysis unit because it had the smallest grid sizes for all move times of 1 to 12 months. The switchgrass also had the shortest distance to move from one mobile pyrolysis station to the next station. To provide sufficient bio-oil production, switchgrass harvest grids were closer than other feedstock harvest grids. Transporting bio-oil using corn stover of three feedstocks had the shortest distances from the mobile pyrolysis station to the nearest oil refinery because several refineries were located in Illinois. The closest refinery was located in

Laramie County, WY for energy sorghum and switchgrass. Corn stover might be the best choice to produce bio-oil for the NC region. If the oil refinery was located in states other than the producing state, the transportation expenses might be high. The GIS program used Model Builder to automate feedstock logistics. Network Analysis was used to calculate the shortest distances. The GIS program used a harvest grid methodology to calculate the biomass available at each pyrolysis station. The size of the harvest grid depends on the move time of the mobile pyrolysis unit. A major strength of the mobile pyrolysis unit is its flexibility to move directly to the production areas avoiding constraints. A GIS analysis was integrated with the economic model to calculate the total cost of harvesting and transporting the biomass and bio-oil. One mobile pyrolysis unit feedstock input rate was 40 tons/day. The mobile pyrolysis units are capable of producing 17,381 barrels crude oil per year. If all feedstocks were pyrolyzed in IL (2008 corn stover production) and NE (2008 energy sorghum and switchgrass production), 14,832,835 (corn stover), 1,262,396 (energy sorghum), and 2,756,005 (swithgrass) of barrels crude oil per year might be produced. Under the same assumption (all feedstocks pyrolyzed), corn stover, energy sorghum, and switchgrass might need 853, 73, and 159 mobile pyrolysis units (stay one location at twelve months) to produce bio-oil per year. For both corn stover (Illinois) and energy sorghum (Nebraska), the probability of success increases when the number of moving times is decreased. The economic model showed a stationary (the mobile pyrolysis unit remains during twelve months) has the highest probability of success, but weather condition and feedstock availability might be constraints.

CHAPTER IV

HYDROLOGIC IMPACTS OF RESIDUE REMOVAL FROM AGRICULTURAL FIELDS FOR BIOENERGY PRODUCTION

Synopsis

Soil and Water Assessment Tool (SWAT) simulations were used to assess the hydrologic impacts of using corn stover as a feedstock for mobile pyrolysis units for bioenergy production in the Spoon River basin in Illinois. The SWAT hydrologic model was used to evaluate changes in streamflow, sediment losses, and corn production rates due to corn stover removal rates of 25%, 50%, 75%, and 100% the Spoon River basin. The SWAT model was calibrated and validated for stream flow (1990 – 2010) and sediment transport (2003 – 2010) using measured data from the USGS station at the outlet of the Spoon River basin. The Nash-Sutcliffe equation (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR) were used to assess accuracy for monthly streamflow and sediment transport in the Spoon River. Streamflows with 25%, 50%, 75%, and 100% residue removal, decreased by 1.03%, 1.86%, 2.55%, and 3.31%, respectively, when compared to no residue removal. The average annual total evapotranspiration (ET) increased slightly 0.46%, 0.82%, 1.10%, and 1.44% for residue removal rates of 0%, 25%, 50%, 75%, and 100%, respectively. The amount of residue removed had a large impact on soil erosion in the Spoon River watershed. The sediment yield increased by 1.6%, 5.5%, 16.1%, and 65.7%, with the residue removal rates of 25%, 50%, 75%, and 100%, respectively. The

tolerance factor (T factor) for the Spoon River basin is 5 tons per acre per year and was exceeded at the 75% removal rate. Crop yields for different residue removal rates slightly decreased compared to yields when no residue was removed. Residue removal rates of 25%, 50%, 75%, and 100%, resulted in 2.8 t/ha, 5.6 t/ha, 8.7 t/ha, and 11.8 t/ha, respectively, of corn stover being removed from the watershed.

Introduction

Global warming and increasing oil prices are contributing to interest in renewable energy sources. Mobile pyrolysis units are capable of producing bioenergy from agricultural sources of biomass. The use of biofuels has the potential to make a significant impact on reducing the net rate of CO_2 emissions. However, crop residues protect and enhance soil quality in agricultural fields by protection from erosive forces, increased organic matter, addition of nutrients, increased biological activity and improved soil structure, that result in improved crop yields *(Hargrove, 1991)*.

The fast pyrolysis process produces bio-oil, syn-gas, and bio-char from biomass. Fast pyrolysis maximizes production of bio-oil with biochar and pyrolysis gas as lower-yielding co-products *(Brown et al., 2011)*. To minimize feedstock transportation costs to a central plant, mobile pyrolysis units could be deployed to locations with high concentrations of feedstocks. Flexibility is a major strength of the mobile pyrolysis units to produce bio-crude oil. The mobile pyrolysis units would convert low density corn stover to high density bio-oil thereby minimizing transportation costs. The deployment of mobile pyrolysis systems to sites close to feedstock sources offers a way to reduce dependence on fossil fuels while limiting greenhouse gas emissions and environmental degradation *(Lal, 2008)*. Corn stover is a potential feedstock for bioenergy production in Iowa and Illinois, due to its abundance in these states *(Wilhelm et al., 2004)*.

The Soil and Water Assessment Tool (SWAT) simulation model was used to assess changes in hydrology, crop production and sediment transport when corn stover is removed and used as a feedstock for mobile pyrolysis units in the Spoon River basin. Specifically, the impacts of corn stover removal on stream flow, sediment transport, and corn production rates were evaluated to ensure that this method of bio-oil production is environmentally sustainable. SWAT is a basin-scale, continuous-time hydrology model that can produce simulation results on a daily, monthly, or annual basis *(Arnold and Fohrer, 2005)*.The model can simulate water quantity as well as water quality *(Saleh et al., 2000)*. The size, scale, and number of sub-watersheds may affect watershed modeling processes and subsequent results. *Jha et al. (2004)* used the SWAT model and focused on four Iowa watersheds ranging in size from 2,000 to 18,000 km^2 for simulating streamflow, sediment, and nutrients for over 30 years. Jha et al. found variation in the total number of subwatershes had little effect on streamflow. However, the optimal threshold subwatershed sizes for sediment, nitrate, and inorganic P required about 3, 2, and 5 percent of the total drainage area for each watershed, respectively *(Jha et al., 2004)*. The SWAT model produced hydrologic budgets and crop yield simulations in the Upper Mississippi River basin (UMRB) without calibration and previous calibrated SWAT simulations in the UMRB were compared to the results of the uncalibrated SWAT model *(Srinivasan et al. 2010)*. *Srinivasan et at. (2010)* reported the uncalibrated model was able to predict the hydrologic budget and crop yields in the UMRB at a satisfactory level when compared to 11 USGS gauges and crop yields in the UMRB *(Srinivasan et al., 2010)*. The Water Erosion Prediction Project (WEPP) model used established and distributed parameters for long term hydrology, land use and soil data *(Abaci and Papanicolaou, 2009)*. The study area was the South Amana Sub-Watershed (SAWS) (~26 km^2) of Clear Creek, IA. The hypothesis for landuse and agricultural management practices tested control of long-term erosion in small agricultural watersheds. Experiments were conducted to use the dominant 2-year crop rations in the SASW; fall till corn-no till bean (FTC-NTB), no till bean-spring till corn (NTB-STC) and no till corn-fall till bean (NTC-FTB); covering about 90% of the total acreage in SASW. This study resulted in a strong correspondence between soil erosion rates and high magnitude precipitation events (mid-April to late July) for all crop rotations. Corn residue stayed on the study area from 40 days to 7 months depending on different crop rotations. This study provided a better understanding of landuse and management practices on water-driven soil erosion in small agricultural watersheds. It quantified the long-term effects of land use and associated management practices on upland erosion at a subwatershed scale under different hydrologic conditions. The long term effects of tillage type and timing for canopy and residue cover shows that land management practices can significantly change the impact of precipitation on soil erosion in small agricultural watersheds.

Soil erosion and land degradation are major issues in Ethiopia. The SWAT model was selected to predict sediment yield in the Anjeni watershed in Ethiopia. The SWAT model simulated stream flow and sediment yields and was calibrated and validated using ten years of monthly meteorological, flow and sediment data. The SWAT model was used to predict monthly sediment yields and assess the impacts of subbasin delineation and slope separation on the prediction of sediment yield. The Nash-Sutcliffe efficiency (NSE) was 0.81 for calibration and 0.79 for validation *(Setegn et al., 2010)*. The calibrated model can be used for further studies on soil erosion and different management practices. *Setegn et al. (2009)* used the SWAT model to provide soil erosion rates in the Lake Tana basin in Bule Nile River Basin, Ethiopia. These simulations were used for making policies and decisions on how to reduce soil erosion at 'hot spots'. Two modeling approaches were applied for simulating soil erosion; (1) SWAT, and (2) a GIS decision support system that used multi-criteria evaluation (MCE). The SWAT model was used to estimate the sediment yield at the subbasin scale and to identify the areas contributing the most sediment in the basin.

Previous studies on residue management

Residue removal effects on erosion are a major concern and corn stover removal have the potential to increase soil erosion on agricultural lands *(Johnson et al., 2010)*. The trend of increasing erosion losses due to corn residue removal was consistent across the different textural classes, a Blount silt loam, a Hoytville clay, and a Oshtemo in a study by *Thomas et al. (2011)*. With the no-till planting practice, the mean annual erosion losses associated with corn stover removal, at the rates of 38%, 52%, and 70%, were significantly higher ($p < 0.05$) than no surface residue removal, regardless of soil types evaluated in this study *(Thomas et al., 2011)*. Other studies predict that 30% stover removal (or less) has little impact on soil erosion or runoff *(USDA NRCS 2006)*. In addition, residues left on the soil surface increased yields for corn and soybean crops when compared with yields under residue removal in Nebraska *(Power et al. 1986)*. The effect of crop residue cover on soil water storage also has great importance. This effect was most pronounced in the drier years when the extra water conserved by residue cover was more critical. The effect on crop yield was also most distinct in drier years when the extra water conserved by residue cover was more significant *(Powel et al., 1886)*. *Power et al. (1986)* found that residue on the field increased yields through water conservation, reduced erosion and increased soil organic matter. On the other hand, residue removal led to faster warming soils in spring, soil organic carbon declines, faster losses of soil moisture, soil erosion increases, and nitrogen and phosphorus mineralization increased *(USDA NRCS, 2006)*.

Previous studies using SWAT investigated residue management and the resulting environmental impacts. The SWAT model was used to evaluate the hydrologic and water quality impacts of corn stover removal at rates of 38%, 52%, and 70% *(Cibin et al., 2011)*. Compared to the baseline scenario(no corn stover removed) at the watershed outlet, 1) streamflow was reduced by 1.4%, 2.0%, and 2.7%, 2) sediment loads increased by 19.7%, 22.5%, and 29.0%, 3) organic nitrogen increased by 0.8%, 2.0%, and 5.5%, 4) mineral phosphorus decreased by 11.7%, 15.5%, and 21.0%, and 5) nitrate concentrations decreased by 2.0%, 3.2%, and 5.3%, with increasing residue removal rates (38%, 52%, and 70%). *Cibin et al. (2011)* concluded that the watershed response to corn stover removal was sensitive to watershed characteristics (slope) and management inputs (amount of fertilizer applied). *Wu and Liu (2012)* selected corn stover and perennial grasses such as switchgrass and miscanthus for the second generation biofuel feedstocks. They evaluated the long-term impacts of biofuel production alternatives (different corn stover removal rates and the potential land cover change) using the SWAT model in the Iowa River Basin (a tributary of the Upper Mississippi River). When corn stover removal rates were 40% and 100% , sediment yield increased (4.7 – 70.6%) due to erosion, decreased water yield (1.2 – 3.2%), and decreased the nitrate nitrogen load (6 – 10.1%) at the watershed scale during an 18-year simulation period (1991-2008) *(Wu and Liu, 2012)*. Using the tolerable soil erosion limit from National Agricultural Statistics Service (NASS), approximately 20-40% of the corn residue produced in the U.S. Corn Belt (top four states: IA, NE, IL, and, IN) can be removed for biofuel production *(Kim and Dale, 2004; Nelson, 2002)*. *Sheehan et al. (2004)* found approximetly 40% of the residue can be safely removed using continuous corn production with a typical tilling operation (mulch till), when compared with 70% under no-till while keeping erosion risks below the tolerable limit in Iowa. *Nelson et al. (2004)* developed a methodlogy to estimate quantites of crop residue that can be removed while keeping rain or wind erosion under or equal to the tolerable soil loss level. Potentaial maximum quantities of residue removal were more than 97 million dry metirc ton/year for a corn-wheat rotation using no-till in Illinois *(Nelson et al., 2004)*. *Sheehan et al. (2004)* found 40% of the residue can be removed under continuous corn production and mulch tillage, compared with 70% removal rates under no tillage operations in Iowa. For both rates, erosion risks were kept below the tolerable limit of 5 t/ac. Maximum corn stover removal quantities for continuous corn crops with different tillage scenarios in Illinois were 50.7, 67.6, and 90.8 million dry Mg/yr harvested for conservation till, reduced/mulch till, and no till, respectively *(Nelson et al., 2004)* . The corn stover removal rates of 40%, 60%, and 80% on average increased sediment losses across all corn areas by 16%, 28%, and 42%, respectively, and decreased total nitrogen (N) losses by 6%, 9%, and 12%, respectively, across the two land types(highly erodible land (HEL) and non-HEL), three soil textural classes clayey, loamy, and sandy), and four hydrologic groups (A – D) *(Meki et al., 2011).*

Study area

This modeling study focused on the effects of corn stover removal on streamflow, sediment yield and biomass production in the Spoon River watershed from January 1990 to September 2010. The Spoon River watershed (shown in Figure 4.1) has an area of 4,241.9 km^2 and is located in Knox, Fulton, Stark, Warren, Peoria, Bureau, Henry, McDonough, and Marshall counties in Illinois. Corn for grain is the primary agricultural crop grown in these counties. The Spoon River watershed is located in the Hydrologic Unit Code (HUC) 07130005and a USGS gauging station (number 05570000 / latitude 40°29'24" / longitude 90°20'25") is located on the Spoon River in the town of Seville in Fulton County. Annual, monthly, and daily discharge, as well as water quality data are available at the National Water Information System from the USGS website for this gauging station *(USGS, 2010b)*, available at http://waterdata.usgs.gov/nwis/. The residue management practices focused on four options, 25%, 50%, 75%, and 100% corn stover removal and compared with no corn stover removal.

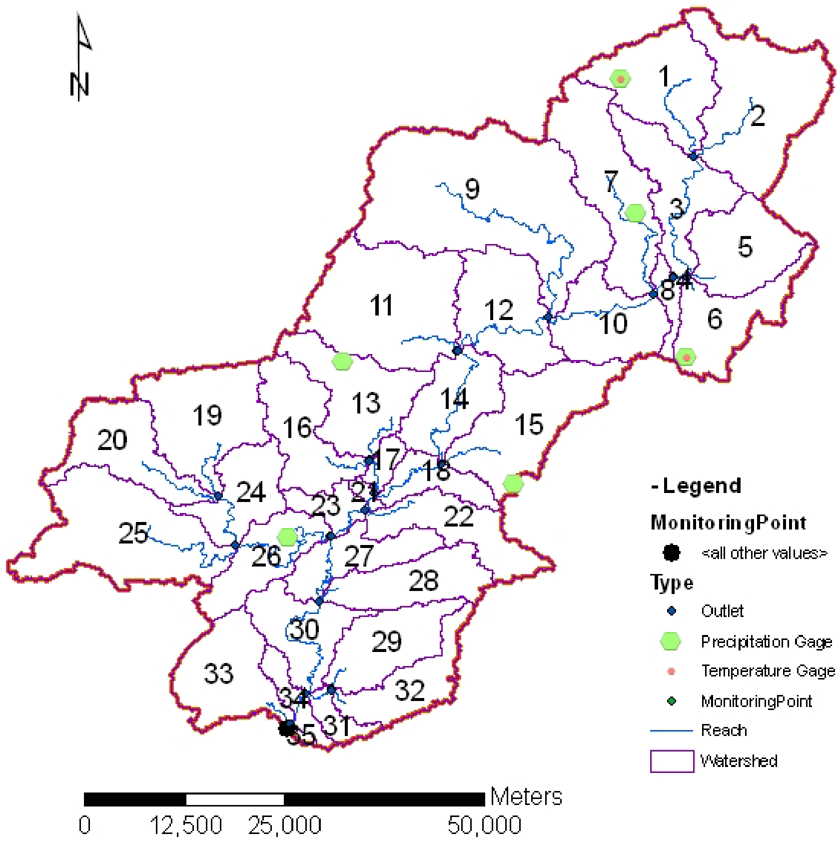


Figure 4. 1 The study area is located in the Spoon River basin in IL. The figure indicates outlet points and stream reaches of each subbasins well as the USGS gauging station at the outlet in Seville, IL, and precipitation and temperature stations in the watershed.

Methods

Model setup

The ArcSWAT 2009 93.7a model was used for this project. The SWAT model generated 35 subbasins (see Figure 4.1) and 384 Hydrologic Response Units (HRU)s for the Spoon River watershed using a threshold area of 10,000 ha when defining the stream network in the SWAT simulation. The SWAT simulation period was from January 1990 to September 2010 and the output was assessed on a monthly basis. The simulation period was selected based on data avaibility from weather stations and from the USGS gauging station (#05570000) at Seville, IL. Suspended sediment discharge, available from March 2003 to September 2010, was also obtained from the USGS National Water Information System at the USGS gauging station ,. The Digital Elevation Model (DEM) used in this study was obtained from the National Hydrography Dataset (NHD) (USGS, 2010a) and ranged from 128 to 292 m. The HRUs were defined using 5% land use, 5% soil class and one slope class. The model performance methods used to assess simulation performance included: coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR).

The locations of actual planted agricultural fields for Illinois were obtained from the 2008 Crop Data Layer (CDL) database *(USDA, 2010a)*. Plant field locations for 2008 were provided as GIS raster files from the spatial analysis research section of National Agricultural Statistics Service (NASS). The CDL program used imagery from the Resourcesat-1 AWiFS and the Landsat 5 TM satellites and provides the CDL anuually with crop specific digital layers in GIS raster formats *(USDA NASS, 2009)*. In the Spoon River watershed in 2008, 42% was planted with corn and 24% planted with soybeanswith 19% forest-deciduous (FRSD) and 11% with hay Agricultural lands were approximentaly 77% of the total study area and the rest of the land uses were residential-low density (URLD), residential-midium density (URMD), and pasture.

The State Soil Geographic (STATSGO) database by the National Resources Conservation Service (NRCS) was used for the soil properties in the SWAT simulation *(USDA NRCS, 2006)*. Major soil types were identified as the Fishhook, Ipava, and Tama and were 38%, 35%, and 10% of the watershed area, respectively. Table 4.1 shows detailed soil properties of Fishhook, Ipava, and Tama for each layer. The hydrologic soil type D has a high runoff potential and a very slow infiltration rate when wet. It has a very slow rate of water transmission. The hydrologic soil type B has a moderate infiltration rate when wetted. The other soil types were Catlin (5.16%), Drummer (3.67%), Lenzburg (3.54%), Beaucoup (2.45%), Fayette (1.08%), and Genesee (0.18%).

Table 4. 1 Soil properties (soil texture, hydrologic soil type, water holding capacity, saturated hydraulic conductivity, USLE soil erodibility factor) of the three main soil types (Fishhook, Ipava, and Tama) in the Spoon River basin in IL.

	Layer #	Soil texture	Hydrologic soil type	Water holding capacity (mm/mm)	Saturated hydraulic conductivity (mm/hr)	USLE_K soil erodibility
Fishhook	I	SIL*	D	0.2	1.2	0.37
	II	SICL*		0.2	0.94	0.37
	III	SICL		0.15	1.4	0.37
Ipava	I	SIL	B	0.21	8.7	0.28
	II	SICL		0.18	0.29	0.43
	III	SICL		0.17	2.7	0.43
Tama	I	SIL	B	0.22	1.9	0.28
	II	SICL		0.2	1.1	0.43
	III	SICL		0.2	0.85	0.43

* SIL: silt loam, SICL: silty clay loam.

Daily precipitation was obtained from National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center *(NCDC, 2010)*. A total of six weather stations (shown in Table 4.2) were used in the Spoon River watershed simulations and wind speed, solar radiation, and relative humidity data were generated by the SWAT weather generator during simulation periods.

Table 4. 2 The names and locations of the weather stations used for precipitation and temperature data in the SWAT simulations in the Spoon River basin.

Station Name	Coordinates	Precipitation	Temperature
Avon 5NE	-90.4º N, 40.7 ºW	yes	no
Kewanee 1E	-89.9 º N, 41.2 º W	yes	yes
Knoxville	-90.3 º N, 40.9 º W	yes	no
Princeville 2W	-89.8 º N, 40.9 º W	yes	yes
Toulon	-89.9 º N, 41.1 º W	yes	no
Yates City	-90.0 º N, 41.8 º W	yes	no

Management operations

Two tillage operations were used for the corn production in the SWAT simulations: field cultivator (15ft) (before applying fertilizer) and subsoil chisel plow (after harvesting). Table 4.3 shows a schedule of the field management operations for corn production that was used in the simulations. Applications of nitrogen (N) and phosphorus (P) were provided by *Dr. Provin (Personal communication, 2011)*. The urea ammonium nitrate solution (32-0-0) is composed of 7.75% ammonium nitrogen, 7.75% nitrate nitrogen, and 16.5% urea nitrogen (http://www.simplot.com/ag_suppliers/ag_crop_nutrition). The triple super phosphate (TSP) (0-45-0) includes available phosphate (P_2O_5) 45% and calcium (Ca) 15.5%. The planting date of corn was set at May 9th. Planting and harvesting dates for corn were obtained from *NASS statistics (2009)* for the counties in the Spoon River watershed and were used for the management operations in SWAT.

Table 4. 3 Corn management operations used in the SWAT simulations of the Spoon River basin.

Date		Management Operation
April	29	Tillage operation (Field Cultivator Ge 15ft)
	30	Fertilizer application
		Urea Ammonium Nitrate Solution, 600 Kg
		Triple Super Phosophate, 150 kg
May	9	Plant/begin growing season: Corn
October	19	Harvest only operation (grain harvest)
	20	Harvest only operation (biomass harvest - different residue removal applied)
	21	Kill/end of growing season
	22	Tillage operation (Subsoil chisel plow)

The SWAT variable, harvest index override, was used to apply different residue removals for harvest operations. The harvest index override is the ratio of biomass removal to total above ground biomass *(Arnold et al. 2011)*. For example, a typical fraction of biomass removed in a cutting for hay is 0.5, which is the default value in the SWAT database. The harvest index for corn (optimal growing condition) was set 0.5, which means the ratio of corn grain (kg) and corn stover (kg) assumed to be one to one *(USDA, 2010b)*. In this study, different fractions of biomass were removed, so the harvest indext override for biomass was set to values of 25%, 50%, 75%, and 100%.

Tile drainage

Subsurface tile drainage was simulated in the poorly drained soils in the Spoon River basin. The poorly drained soils in the Spoon River basin were identified as the FISHHOOK, IPAVA, DRUMMER soils *(USDA NCSS, 2011)*. In the tile drainage simulations, subsurface water flows to the subbasin outlet from the tile drainage system. The depth to subsurface drain (DDRAIN) was set to 3 ft (914.4 mm) and the time to drain soil to field capacity (TDRAIN) and drain tile lag time (GDRAIN) were set to 24 and 2 hours in the SWAT simulation.

Sensitivity analysis

A sensitivity analysis was performed to identify the primary SWAT input parameters that affect model simulations for monthly streamflows and sediment. The sensitivity analysis routine in SWAT uses the Latin Hypercube One-factor-At-a-Time (LH-OAT) method, proposed by *(Morris, 1991)*. The Latin-Hypercube performs random sampling to allow a robust analysis that does not require too many runs. The concept of the Latin-Hypercube Simulation is to use a stratified sampling approach for efficient estimation of the output statistics, based on the Monte Carlo Simulation *(McKay, 1988)*.

Streamflow and sediment

Daily streamflow data from 1977 to 2010 from the USGS gaguing station was used in the sensitivity analysis. A total of 26 parameters for flow analysis and six parameters for sediment analysis were used. The most sensitive parameter for streamflow turned out to be the curve number (CN2). Other sensitive parameters were soil evaporation compensation factor (ESCO), effective hydraulic conductivity (Ch_K2) in the main channel alluvium , Manning's "n" value for the main channel (Ch_N2), threshold depth of water in the shallow aquifer required for return flow to occur (Gwqmn), maximum canopy storage (Canmx), and available water capacity (Sol_Awc) of the soil layer. Daily sediment data from 2003 to 2009 the USGS gauging station was used in the sensitivity analysis for sediment yields. The most sensitive parameters for the simulation of sediment transport were the linear parameters for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing (SPCON), channel cover factor (Ch_COV), exponent parameter for calculating sediment re-entrained in channel sediment routing (SPEXP), USLE equation support practice factor (USLE_P) and minimum value of USLE C factor for water erosion applicable to the land cover (USLE_C).

Baseflow analysis

Automated methods for estimating baseflow and groundwater recharge were used to increase the accuracy of the SWAT model simulations (http://swatmodel.tamu.edu/software/baseflow-filter-program). The baseflow filter program assesses the separation of the baseflow from streamflow to determine the contribution from overland flow during a rainfall event in the watershed *(Arnold and Allen, 1999)*. Daily streamflow data (1977 – 2010) at the USGS gage station (at the outlet point) was used for the input dataset. The results of the baseflow separation analysis indicated that fractions of streamflow contributed by baseflow was estimated to range from 0.40 and 0.64. In SWAT, the base flow recession variable (ALPHA_BF) was set to 0.0317 (the result of the baseflow filter program), which is a direct indicator of groundwater flow response to changes in recharge. The model input variable for ground water delay (GW_DELAY) was set to 73 days, which defines number of days for the baseflow recession to decline through one log cycle *(Arnold et al., 1995)*. These groundwater parameters represent the lag time of water movement from the shallow aquifer, the vadose and groundwater zones. Groundwater flows depend on the water depth, soil profiles, and the hydraulic properties of the geologic formations.

Model performance

Model evaluations were used to verify the robustness (or goodness of fit) of the model. In this study, four model evaluation methods were used: coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR).

The coefficient of determination (R^2) is a measure of the strength of the linear relationship between observed and simulated data. A coefficient of determination (R^2) describes the proportion of the variance in measured data, and ranges from 0 to 1. Higher values have less error variance. If the R^2 value is close to zero, the model prediction is considered “unacceptable or poor ” *(Santhi et al., 2001)*. The Nash-Sutcliffe efficiency (NSE) is calculated as the ratio of residual variance to measured data variances *(Nash and Sutcliffe, 1970)*. It is recommended for use by *American Society of Civil Engineers (ASCE) (1993)* and *Legates and McCabe (1999)*. *Servat and Dezetter (1991)* found the

NSE to be the best objective function for reflecting the overall fit of a hydrograph. NSE ranges from -∞ to 1. The closer the NSE value is to 1, the more accurate the model is. The NSE could be negative, which is an undesirable result. Next, the percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts *(Gupta et al., 1999)*. The optimal value of PBIAS is 0. Positive values and negative values indicate that the model underestimates bias or overestimates bias, respectively *(Gupta et al., 1999)*. The RSR method is calculated as the ratio of the Root Mean Square Error (RMSE) and standard deviation of the observed data *(Moriasi et al., 2007)*. RMSE is one of the most popular error index statistics *(Chu and Shirmohammadi, 2004)*.The optimal value of RSR is 0. The lower RSR (lower RMSE) values are, the better model performance is. In general for streamflow, a model simulation can be judged as satisfactory if NSE > 0.50 and RSR ≤ 0.70, and PBIAS = ±25%. For the simulation of sediment transport a NSE > 0.50, RSR ≤ 0.70, and PBIAS = ±55% are considered to be satisfactory *(Moriasi et al., 2007)*.

Results

Calibration parameters

The SWAT calibration method compared simulated streamflows and sediment yields from SWAT to observed values from the USGS gauging station. Model calibrations were performed manually by adjusting hydrologic and sediment parameters based on the sensitivity analysis. Table 4.4 shows the model input parameters used in the SWAT calibration process. The SWAT model was calibrated over 9 years (1992 - 2000) and validated over 10 years (2001 - 2010) for monthly streamflow. Sediment yields were only calibrated over 6 years (2004 - 2009), due to lack of measured data. The calibration process was basically a trial-and-error process to yield a good fit of model simulations to measured data. As mentioned earilier, four different methods were used to evalute calibration and validation for streamflow and sediment yield. The primary SWAT variable adjusted during the calibration and the most sensitive parameter was curve number (CN).

Table 4. 4 SWAT model input parameters that were adjusted during the calibration for streamflow and sediment transport.

Variable	**Description**	**.file**	**Calibrated Value**	**Range**
Streamflow				
CN2	Curve number	.mgt	10% increase (Corn 85 Soybean86 Forest 73 Hay 65)	
ESCO	Soil evaporation compensation coefficient	.hru	0.85	0.01 - 1
IPET	PET method (water balance)	.bsn	Hargreaves	
IRTE	Channel routing (reaches) method		Muskingum	
SFTMP	Snowfall temperature (ºC)		1	
SMTMP	Snow melt base temperature (ºC)		-1	
SMFMX	Melt factor for snow on June 21(mm H2O/ºC-day)	.bsn	2.5	
SMFMN	Melt factor for snow on December 21 (mm H2O/ºC-day)		2.5	
CH_K(1)	Effective hydraulic conductivity in tributary channel alluvium (mm/hr)	.sub	0.5	0.025 – 150
CH_N(1)	Manning’s “n” value for the tributary channel	.sub	0.03	0.01 – 0.07
CH_N(2)	Manning’s “n” value for the main channel	.rte	0.05	0.01 – 0.07

Table 4. 4 Continued

Variable	Description	.file	Calibrated Value	Range
Tile Drainage				
DDRAIN	Depth to the sub-surface drain (mm)	.mgt	914.4	0 – 2000
TDRAIN	Time to drain soil to field (hours)	.mgt	24	0 – 72
GDRAIN	Drain tile lag time (hours)	.mgt	2	0 – 100
Groundwater				
Alpha_bf	Base flow recession	.gw	0.0317	0 - 1
GW_DELAY	Ground water delay	.gw	73	0 - 500
Sediment				
USLE_P	Universal Soil Loss Equation	.mgt	0.8	0.1 - 1
SPCON	Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing	.bsn	0.01	0.0001 – 0.01
SPEXP	Exponent parameter for calculating maximum amount of sediment that can be reentrained during channel sediment routing	.bsn	1.5	1.0 – 2.0
CH_COV1/2	Channel cover factor	.rte	0.4/0.5	0.01 – 0.5

Model evaluation

The SWAT model was calibrated from January 1992 to December 2000 and validated from January 2001 to September 2010. A “warm-up” period from 1990 to 1991 was used to let the model come into equilibrium. The Nash-Sutcliffe coefficient (NSE) was 0.66 for the calibration period (1992-2000) and 0.84 for the validation period (2001-2010). Table 4.5 shows each model performance after running simulations for streamflow and sediment. The monthly stream flow matched the measured values for calibration period with R^2, NSE, PBIAS, and RSR equal to 0.69, 0.66, 8.8%, and 0.58, respectively. For the validation period, the simulated and the observed monthly stream flow showed very good as indicated by R^2, NSE, PBIAS, and RSR equal to 0.87, 0.84, 10.1%, and 0.40, respectively. General performance ratings of NSE values for streamflow were good for calibration and very good for validation, based on *Moriasi et al. (2007)*. The PBIAS values for streamflow were very good and good for the calibration and validation period, and RSR values are good for the calibration period and very good for the validation period. The model performance values for sediment were satisfactory (RSR), satisfactory (NSE), and very good (PBIAS), respectively. The performances of streamflow calibration were good (NSE), very good (PBIAS), and, good (RSR), respectively. Overall, the model performance for stream calibration was good. Model performance ratings for sediment calibration were not the same for all model performance methods. However, in general the performance should be described conservatively as satisfactory for the sediment calibration.

Table 4. 5 Model performance for streamflow simulation after calibration and validation. Also included is the model performance for sediment yield after calibration. Four statistical methods (R^2, NSE, PBIAS, and RSR) were used to evaluate model performance.

	$\mathbf{R^2}$	**NSE**	**PBIAS**	**RSR**
Streamflow				
Calibration	0.69	0.66 (good)	8.8% (very good)	0.58 (good)
Validation	0.87	0.84 (very good)	10.1% (good)	0.40 (very good)
Sediment				
calibration	0.63	0.63 (satisfactory)	1.8% (very good)	0.61 (satisfactory)

Streamflow and sediment transport

The monthly observed and simulated streamflows and precipitation are shown in Figure 4.2. Observed and simulated streamflow patterns closely match the precipitation patterns in the Spoon River basin. Monthly precipitation ranged from 7.4 to 290.8 mm. Monthly simulated streamflows ranged from 1.3 to 197.1 m^3/s, and the monthly observed streamflows ranged from 1 to 228.6 m^3/s. SWAT simulated streamflow generally captured the observed peak flows although simulated values underpredicted the highest discharge. Maximum annual simulated streamflows were underestimated compared to the maximum annually observed streamflows for 13 years during the simulation period. Maximum annual precipitation was 290.8 mm in 1993, and minimum annual precipitation was 7.4 mm in 1999 during the simulation period (1990-2010).

Monthly observed and simulated sediment yields for the calibration period are shown in Figure 4.3. The maximum annual sediment yield for the USGS gauging station and SWAT simulations were 1,819,870 tons and 1,710,520 tons, respectively, in 2009. More sediment transport typically occurred in May and June of each year, when on average these months accounted for 33.2% and 32.7% of the total annual observed (USGS) and the simulated (SWAT) load in the Spoon River watershed. On a monthly basis, USGS and simulated sediment yields followed monthly observed and simulated streamflow patterns, with peak times during the sediment calibration periods (2004 – 2010).

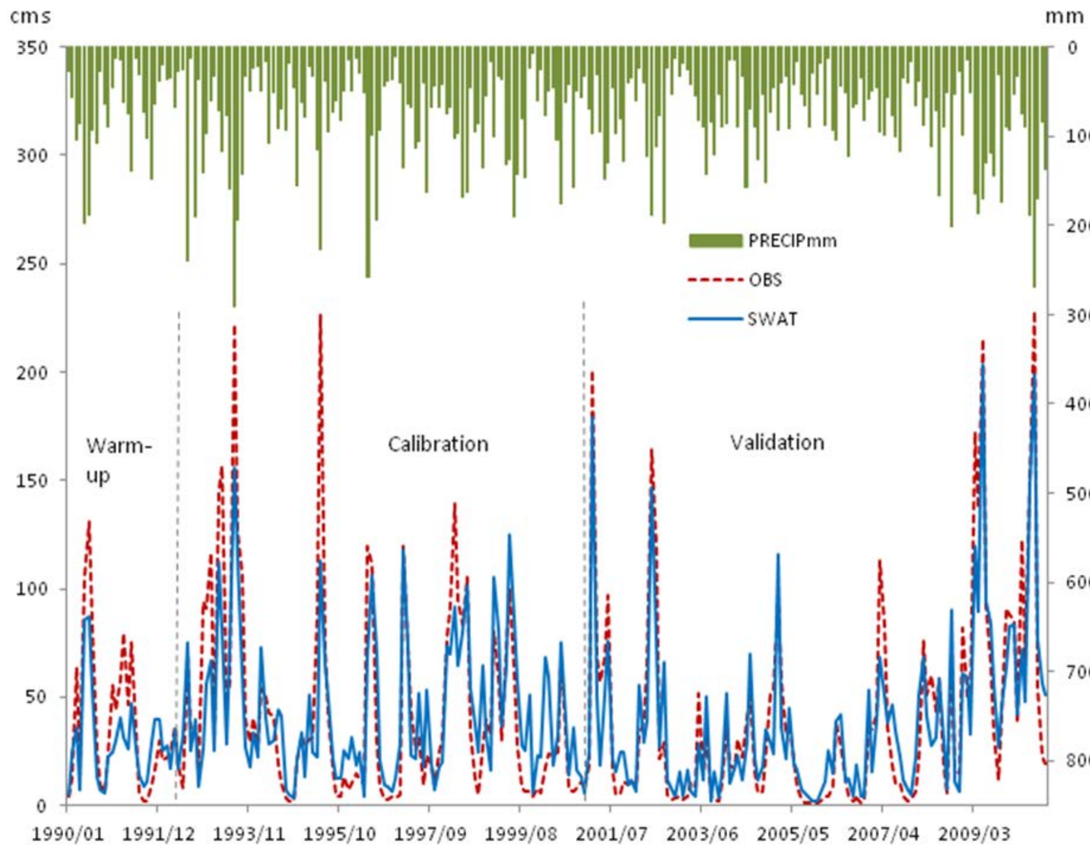


Figure 4. 2 Monthly observed and simulated streamflow for the warm-up, calibration, and validation periods and precipitation data in the Spoon River Basin from 1990 to 2010

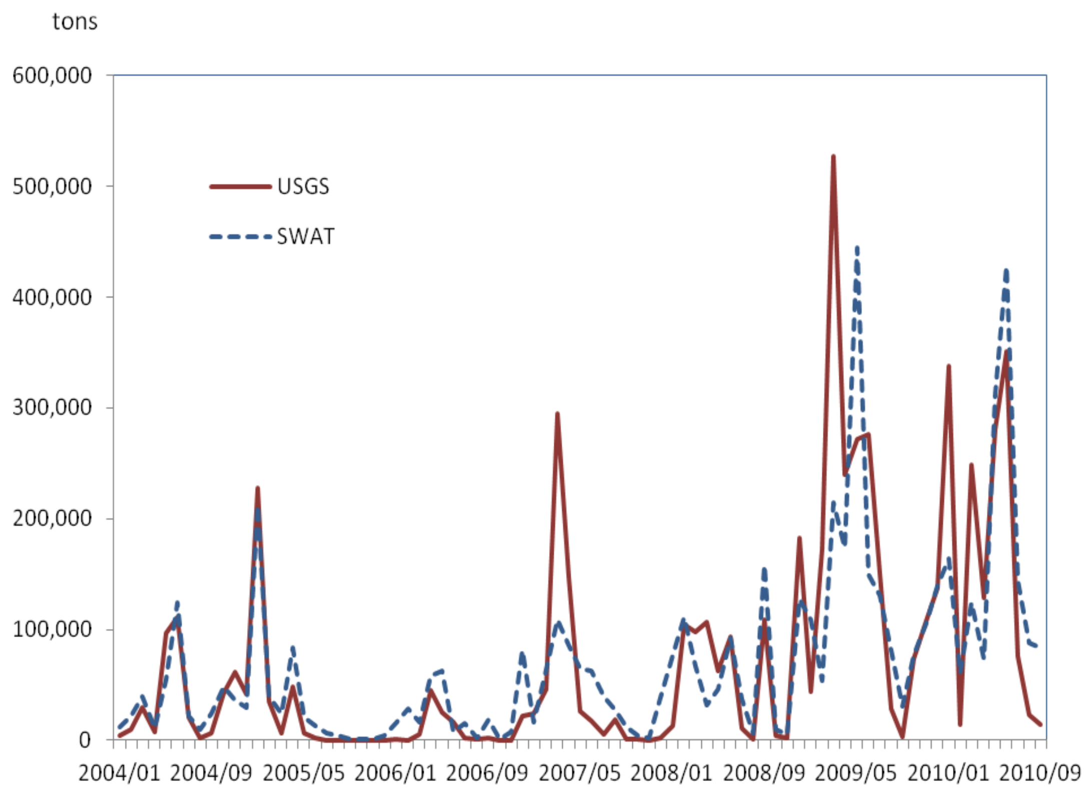


Figure 4. 3 Monthly USGS and simulated sediment yields for the calibration period (January 2004 – September 2010).

Effects of residue removal rates on hydrology

In this study, the effects of corn stover removal rates of 25%, 50%, 75%, and 100% were evaluated using SWAT. The average annual water yield with different residue removal rates (0%, 25%, 50%, 75%, and 100%) in the Spoon River basin are shown in Figure 4.4. These simulationswere based on the 21-year period from 1990 to 2010. Water yields for 25%, 50%, 75% and 100% removal rates decreased by 0.97%, 1.68%, 2.11%, and 2.54% respectively, compared to no residue removal water yield. The following equation was used to estimate the water yield.

WYLD = SURQ + LATQ + GWQ – TLOSS Eq. 4.1

Where, SURQ is surface runoff, LATQ is lateral flow contribution to stream, GWQ is groundwater contribution to streamflow, and TLOSS is transmission losses.

Figure 4.5 shows the average annual total evapotranspiration (ET) for different residue removal rates (0%, 25%, 50%, 75%, and 100%). The average annual total ET increased slighty 0.44%, 0.75%, 0.95% and 1.12% corresponding to the four corn stover removal rates of 25%, 50%, 75%, and 100%, respectively. Residue left on the ground has the role of decreasing ET while the water yield increased with residue removal rates. Figure 4.6 shows these change rates for streamflows, water yield, and ET correspoinding to corn stover removal rates (25%, 50%, 75%, and 100%).

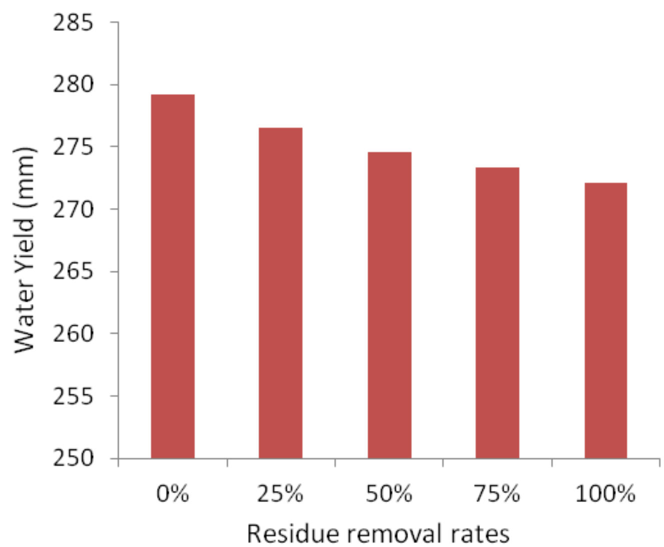


Figure 4. 4 Average annual water yield (mm) for different residue removal rates from 1990 – 2010 in the Spoon River basin. Water yields decreased by 0.97%, 1.68%, 2.11%, and 2.54 compared to the water yield for no residue removal.

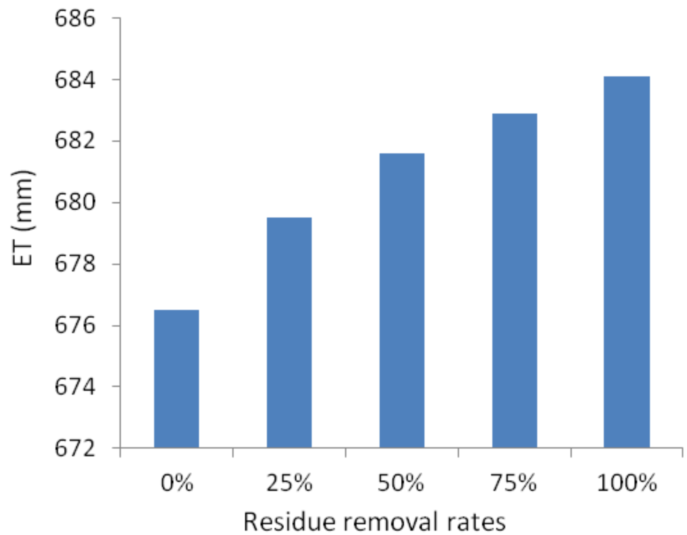


Figure 4. 5 Average annual total evapotranspiration (mm) for different residue removal rates from 1990 – 2010 in the Spoon River basin. The ET increased slighty 0.44%, 0.75%, 0.95% and 1.12% compared to ET for no residue removal.

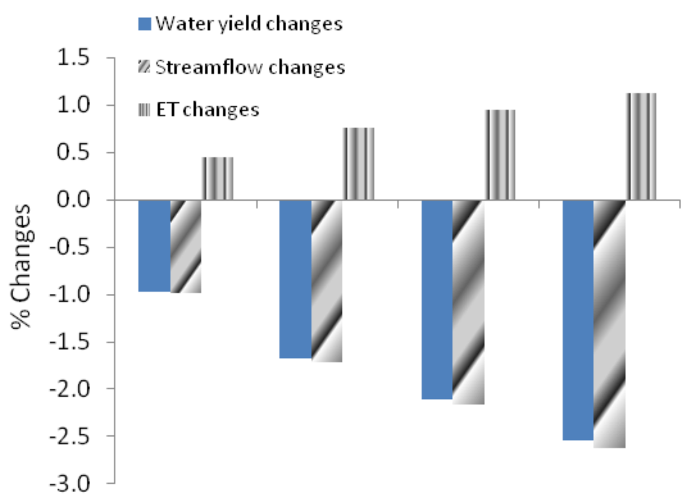


Figure 4. 6 Streamflow, water yield, and ET changes for corn stover removal rates of 25%, 50%, 75%, and 100% from 1990 – 2010 in the Spoon River basin.

Differences in sediment losses

Figure 4.7 shows the average monthly sediment yield in the watershed.

Compared to sediment yield for no residue removal, the sediment yield with 25%, 50%, 75%, and 100% residue removal rates increased by 2.4%, 7.1%, 18.1%, and 65.1%, respectively. As the corn stover removal rate increased, the ground surface was less protected. The National Resources Inventory (NRI) glossary defined the soil loss tolerance factor (T factor) as the maximum rate of annual soil loss that premits crop productivity to be sustained economically and idefinitely on a given soil *(USDA NRCS, 2009).* According to the Web Soil Survey (WSS) *(USDA NRCS, 2011)*, the average T factor is 5 t/ac per year for the Spoon River basin. The sediment yield for 75% residue removal rate was 5.0 t/ac, which exceeded the soil loss tolerance factor (T factor). Therefore, a residue removal rate of 75% will produce excessive sediment yields in the Spoon River watershed. Soil loss increased with decreasing residue remaning on the soil surface. The average monthly sediment yield over 21 years (1990 – 2010) is shown in Figure 4.8 As the corn stover removal rates increased, the sediment yields also increased. The highest sediment yields occurred in May and June during the growing season. The sediment yields were associated with rainfall data, because peaks for sediment yields and rainfall occurred in May and June. Figure 4.9 shows average yearly sediment yields for 25%, 50%, 75%, and 100% residue removal rates from 1990 to 2010 at the outlet point in the Spoon River basin. The average yearly sediment yield ranged from 0.6 to 5.14 t/acres with the 25% residue removal rate, and the average yearly sediment yield ranged from 0.73 to 8.71 t/acres with the 100% residue removal rate. The sediment yield for 100% residue removal rate exceeded the soil loss tolerance factor (T factor) at the outlet point of the subbasin 5 and 6.

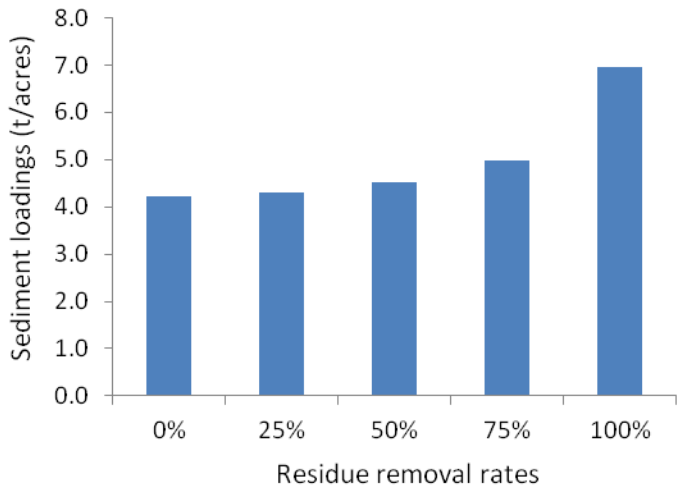


Figure 4. 7 Average annual sediment yields with different corn stover removal rates (no removal, 25%, 50%, 75%, and 100% removal) at the Spoon River watershed over the simulation period (1990-2010).

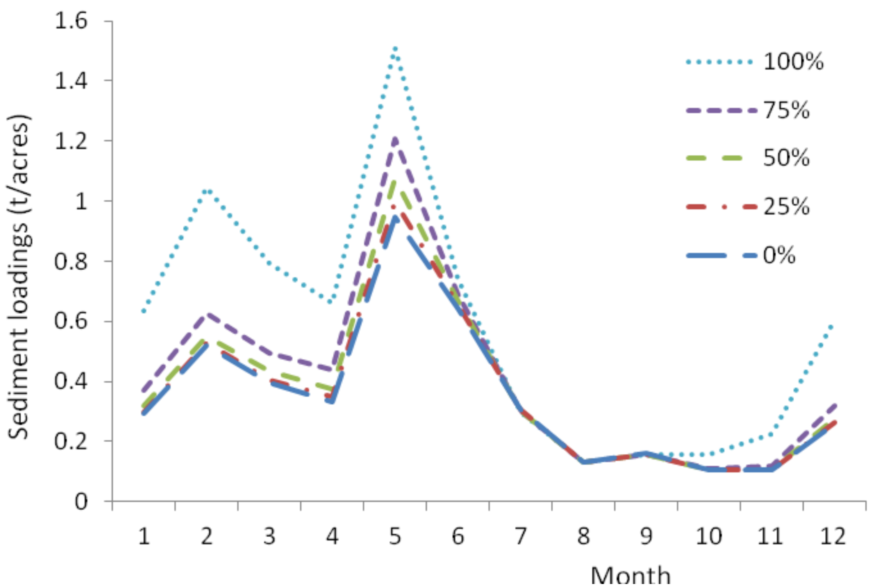


Figure 4. 8 Average monthly sedimet yields for 25%, 50%, 75%, and 100% residue removal from 1990 – 2010 in the Spoon River basin.

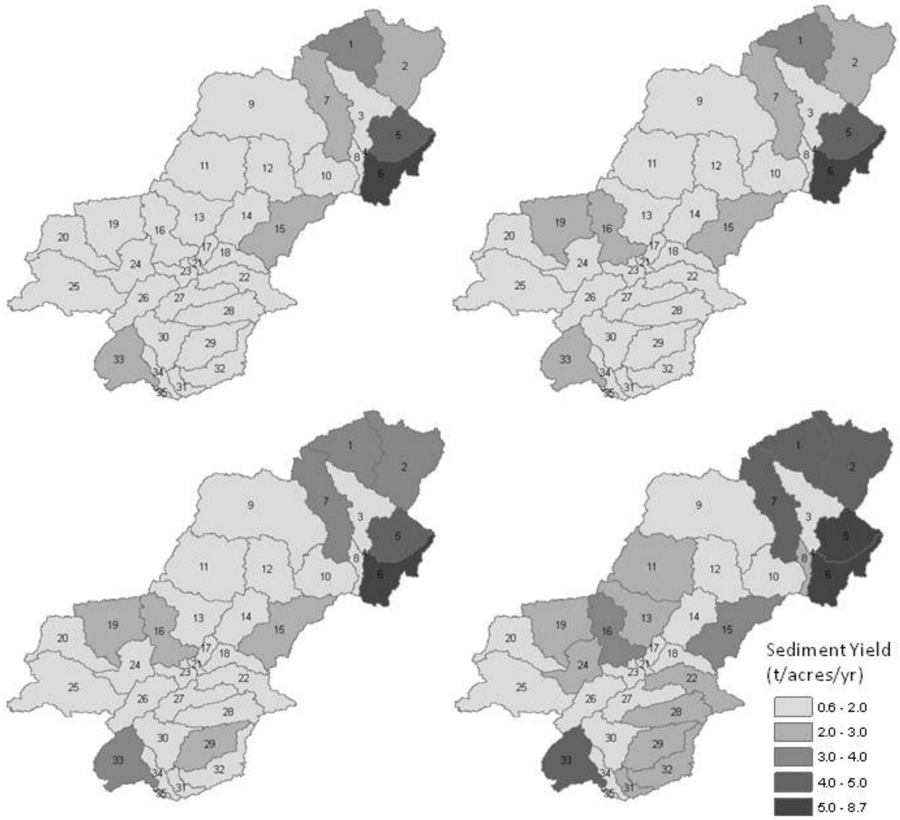


Figure 4. 9 Average monthly sedimet yields for 25%, 50%, 75%, and 100% residue removal from 1990 – 2010 in the Spoon River basin.

Crop growth

Corn yield statistics were obtained from NASS for the nine counties (Bureau, Henry, Stark, Knox, Marshall, Warren, Peoria, Fulton, and McDonough in Illinois) in the Spoon River watershed. The average harvest yield from NASS was 10.63 tons/ha (169.4) bushel/acres over 10 year average (1999-2008). The average corn yields from the SWAT simulations from 1990 – 2010 in the Spoon River basin were 10.61 t/ha (169.0 bushel/acres). Therefore the SWAT simulation results for crop yield were very close to the actual yields in the Spoon River watershed. In the SWAT simulations, the crop management operations were divided into two parts; grain harvest and biomass harvest. After grain was harvested the biomass was harvested with different residue removal rates (0%, 25%, 50%, 75%, and 100%). The harvest index was set to 0.5, which means that the ratio between corn for grain and biomass was assumed to be one to one. Grain and biomass harvest yields (t/ha) in the watershed scale are shown in Figure 4.10. Biomass yields were 2.9, 5.6, 8.7, and 11.8 t/ha for corn stover removal rates of 25%, 50%, 75%, and 100%, respectively.

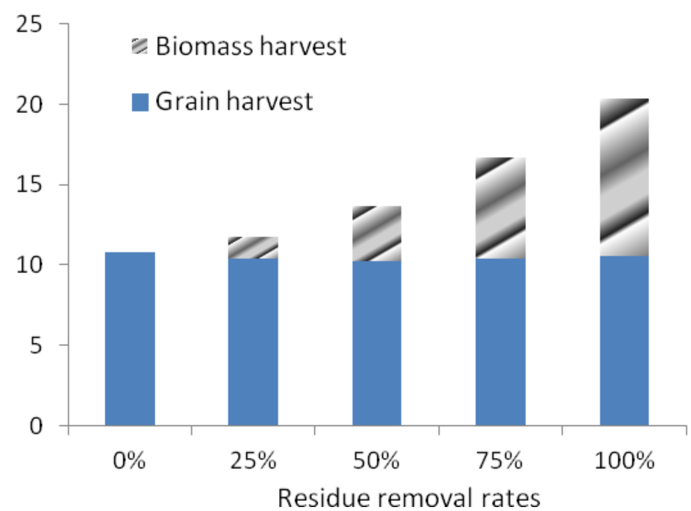


Figure 4. 10 Annual grain and biomass harvest yields (t/ha) with different residue removal rates (no removal, 25%, 50%, 75%, and 100% residue removal) in the Spoon River Basin from 1990 – 2010.

Conclusion

The SWAT model was used to evaluate streamflow, sediment, and crop/biomass yields in the Spoon River basin in IL, in response to corn stover removal for bioenergy production. The outlet point of the watershed was located at the USGS gauging station

(#0557000) in Fulton County, IL. Four different residue removal rates (25%, 50%, 75%, and 100%) were compared to no residue removal for both water quantity and water quality. The Spoon River basin was chosen since Illinois is a major corn producing state and the availability of measured streamflow and sediment data at the USGS station. Corn fields accounted for 42% of the entire watershed. The SWAT model was calibrated (1992-2000) and validated (2001-2010), using streamflows and sediment yield from the USGS gauging station (0557000) at the watershed outlet. The goodness of fit was verified using four different statistical parameters, coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR). For the calibration period, a comparison of simulated and observed streamflows produced R^2, NSE, PBIAS, and RSR values of 0.69, 0.66, 8.8%, and 0.58, respectively. The monthly streamflows matched the measured values for the validation period with R^2, NSE, PBIAS, and RSR values equal to 0.87, 0.84, 10.1%, and 0.40, respectively. The goodness of fit was even better for the validation period (2001-2010). As bioenergy is needed to produce renewable energy, the hydrologic impacts of biomass removal from agricultural fields must be evaluated to ensure a sustainable bioenergy system. When the residue removal rates increased by 25%, 50%, 75%, and 100%, streamflow slightly decreased 0.99%, 1.72%, 2.17%, and 2.62%, respectively. However, average annnual total evapotranspiration (ET) increased 0.44%, 0.75%, 0.95%, and 1.12%, with the residuie removal rates of 25%, 50%, 75%, and 100%, respectively. Residue left on the ground was related to decreasing ET while the water yield increased with residue removal rates.

With the residue removal rates of 25%, 50%, 75%, and 100%, the sediment yield increased by 2.4%, 7.1%, 18.1%, and 65.1%, respectively. The residue removal rates were significantly related to soil erosion. Erosion occurred when residue removal rates increased over the agricultural lands.The tolerance factor (T factor), 5 tons per acre per year, was exceeded at the 75% removal rate in the Spoon River basin. The SWAT simulation showed sediment loadings with different residue removal rates for 35 subbasins, and residue could be careflly removed for sediment yields exceeding 5 tons per acre per year. To produce bio-oil from feedstocks sustainably, residue removal rates and impacts on water and erosion need to be considered to minimize the negative impacts of producing bio-oil. In the future, conservation practices such as contour cropping or tillage operation may be needed to control increased erosion rates due to residue removal.

CHAPTER V

HYDROLOGIC IMPACTS OF BIOCHAR APPLICATION TO AGRICULTURAL SOILS

Synopsis

The sustainable production of agricultural feedstocks for bioenergy production using pyrolysis is required for a renewable bioenergy source. Biochar is a byproduct of the pyrolysis process and must be recycled as a soil amendment on feedstock production fields for agronomic and economic benefits. The laboratory experiments have been conducted on the soils amended with biochar to determine changes in basic soil properties. Different biochar rates were applied to two different soil types, a Booneville loam and Burleson clay. Laboratory results showed that water holding capacity increased, the saturated hydraulic conductivity increased and bulk density decreased after incorporation of biochar. Using the laboratory results, the Soil and Water Assessment Tool (SWAT) model was used to evaluate hydrologic impacts, sediment losses, and changes to crop yields due to land applications of biochar to corn fields in the Spoon River Basin in Illinois. Model simulations indicate that applying biochar at a rate of 128 Mg/ha, the cumulative monthly water yield decreased by 5.3%, the cumulative amount of soil water at the end of each month increased by 3.5%, the evapotranspiration (ET) increased by 1.8% , and the cumulative sediment yields decreased by 5.6% in the Spoon River Basin.

Introduction

Pyrolysis uses agricultural feedstocks to produce bioenergy in the form of bio-oil and synthesis gas (syngas). However, as much as 30% of the feedstock used in pyrolysis ends up as biochar. The beneficial reuse of this biochar byproduct as a soil amendment and nutrient source is critical to the sustainability of this bioenergy system. Pyrolysis is the thermal decomposition of biomass without oxygen. Pyrolysis technologies can be classified by the reaction time of the pyrolysis materials (e.g. slow and fast pyrolysis process) and heating methods *(Meyer et al., 2011)*. The temperatures of slow and fast pyrolysis are typically around 400 ºC and 500 ºC, respectively. Typical residence time of slow pyrolysis is from minutes to days. However, typical residence time of the fast pyrolysis is less than one second (Meyer et al., 2011). Fast pyrolysis maximizes production of bio-oil and results in lower yields of the biochar and pyrolysis gas co-products *(Brown et al., 2011)*. The non-condensable gases and biochar from pyrolysis are used to provide process heat and power for the National Renewable Energy Laboratory *(NREL) (2005)*. Lignocellulosic residues of cereals crops such as corn, wheat, barley, oats, and rice are needed for improving and sustaining soil quality *(Lal, 2008)*. Excessive (25%) and continuous (> 10 yr) removal of crop residues can degrade soil quality, reduce agronomic productivity, accelerate soil erosion, and increase non-point source pollution *(Lal, 2008)*. Therefore it is important to identify sources of biomass for use as biofuel feedstocks that do not cause soil and water quality problems. This may include residues such as rice husksand straw, wheat straw, pistachio shells, rapeseed plant straw and stalk, and corn stover *(Capunitan and Capareda, 2012)*. Corn is the most widely planted crop in Midwest U.S., and corn stover consists of the above-ground portion of the corn plant including the stalk, leaves, cob, and husk *(Demirbas, 2008)*. *Capunitan and Capareda (2012)* found that when corn stover was used as a feedstock for pyrolysis, it produced a valuable bio-oil. However, harvesting agricultural crop residues for producing bioenergy may have negative impacts on soil and environmental degradation *(Lai, 2004; Wilhelm et al., 2004; Lal and Pimentel, 2007)*. According to residue removal studies *(Civin et al., 2012; Wu and Liu, 2012)*, as the residue removal rates increased, sediment yields also increased. Biochar can be returned to agricultural production fields as a soil amendment and has been proposed as a way to establish a sustainable biomass production system *(Fowels 2007; lehmann 2007; laird 2008)*. Some researchers suggest that biochar application as a soil amendment has the potential to increase nutrients, water use efficiency, and crop productivity *(Glaser et al, 2001; Liang et al., 2006)*.

Soil properties

Application of biochar as a soil amendment is hypothesized to increase plant available water, build soil organic matter, improve nutrient cycling, lower bulk density, and reduce leaching of pesticides and nutrients to surface and ground water *(Laird, 2008)*. Most the Ca, Ma, K, P, and plant micronutrients, and about half of N and S in the biomass feedstock are partitioned into the biochar fraction during the pyrolysis process *(Liang et al, 2006; Cheng et al., 2008)*. *Liang et al. (2006)* suggested that black carbon biochar might significantly affect nutrient cycling during biogeochemical processes in soils. Biochar applications also decrease soil bulk density and increase cation exchange capacity, nutrient cycling, and water holding capacity *(Laird, 2008; Liang et al., 2006).* The bulk density of biochar is low (approximately 0.2 g/cm^3) and can lower the bulk density of clay soils and increase the water holding capacity of sandy soils *(Laird 2008).* Biochar had a significant effect of increasing available water holding capacity due to increasing mesoporosity at the expense of macroporosity, without detrimental effects on chemical or microbial properties *(Jones et al., 2010). Laird et al. (2010)* investigated the impact of biochar amendments (0, 5, 10, and 20 g-biochar kg^{-1} soil) on the quality of a Clarion soil (taxonomic class- fine-loamy, mixed, superactive, mesic Typic Hapludolls) in Boone County, Iowa. Their results showed soil bulk density decreased with time when compared to the un-amended soil. In addition, soils amended with biochar contained more water (up to 15%) when drained by gravity to equilibrium and had more water retention for bar -1 (13% greater) and bar -5 (10% greater) pressures. Saturated hydraulic conductivity had no change, but total N increased (7%) and as did organic C (69%). Therefore, biochar amended soils have the potential to improve the fertility of Midwestern agricultural soils *(Laird et al., 2010).* Biochar applications improved the saturated hydraulic conductivity of the top soil and the xylem sap flow of the rice plant, enhanced grain yields, and enhanced the response to N and P chemical fertilizer treatments *(Asai et al., 2009).* Compared to other soil organic matter, biochar adsorbs cations *(Sombroek et al., 1993)* because of its surface area, greater negative surface charge and greater charge density *(Liang et al., 2006).* In contrast to other organic matter in soil, biochar also strongly absorbs phosphate, even though it is an anion

(Lehmann, 2007). Two aspects of biochar make it a good soil amendment: 1) its high stability against decay, and 2) its superior ability to retain nutrients as compared to other forms of soil organic matter. In addition, biochar added to soil has other benefits such as mitigation of climate change through carbon sequestration, improvement of soils, and reduction of environmental pollution *(Lehmann, 2007)*.

Crop yield

Biochar has been shown to reduce impact of raindrops, decrease runoff and improve water infiltration rate *(Lal, 2008)*. Although biochar could be used to generate energy, application of the biochar to soil may be better for the aspect of sustainability *(Laird, 2008)*. According to *Lehmann et al. (2006)*, crop growth responds positively to bio-char application up to 50 Mg C ha^{-1}.Crop growth was reduced only when there are very high applications of biochar greater than 140 Mg C ha^{-1} for most plant species and soil conditions *(Lehmann et al., 2006)*. *Asai et al. (2009)* investigated the effect of biochar application on soil physical properties and grain yields of upland rice in northern Laos during the wet season in 2007. Three different experiments were conducted at 10 sites, including biochar application rates from 0 to 16 t/ha, different fertilizer application rates of N and P, and two rice cultivars (improved and traditional). The main physical processes of biochar that improve crop yields are the ability to retain nutrients by absorption, increased available water holding capacity due to changes in porosity and reduced soil strength *(Graber et al.2010)*. *Yamato et al. (2006)* showed that biochar application to the soils increased crop yields in South Sumatra, Indonesia. Therefore biochar applications may increase crop productivity and reduce agricultural inputs *(Laird et al., 2009)*. According to *Saito's study (2006)*, grain yield increased with 4 and 8 Mg/ha biochar application rates, but grain yields decreased at the 16 Mg/ha rate. However, immobilization of N might be a major limiting factor to enhanced agricultural production *(Saito 2006)*.

Carbon sequestration

Biochar contains a large amount of carbon and has the potential to sequester carbon in the soil for long time periods. Therefore carbon emissions are avoided and carbon trading may be applicable in the future *(Lehmann et al. 2006)*. From an environmental perspective, biochar as a soil amendment has the benefit of carbon sequestration. Biochar composed of 38% carbon from plant biomass would be sequestered in the soil and not emitted to the atmosphere after plant decay, therefore reducing net greenhouse gas (GHG) emissions *(Chan and Xu, 2009)*. The reduction of GHG emissions from biochar applications to the soil were estimated to be approximately 864 kg of CO_2 per equivalent metric ton of dry feedstock *(Roberts et al., 2010)*. *Roberts et al. (2010)* found that 62 - 66% of the emission reductions were from permanent sequestration of carbon in biochar.

Study objective

The objective of this study was to use the SWAT model to determine the hydrological effects of biochar applications on corn production fields in IL. The study area for this SWAT modeling project was located in the Spoon River Basin in IL. A previous SWAT study in the Spoon River Basin focused on changes of water quantity and quality due to residue removal of corn stover for bioenergy production (Chapter IV). The previous study found that streamflows slightly decreased with increasing residue removal rates (25%, 50%, 75%, and 100%). However, the amount of residue removed had a large impact on the soil erosion in the Spoon River Basin. When the residue removal rates increased, sediment yields also increased 1.6% (25% removal) to 65.7% (100% removal). In this study, biochar was returned to the corn fields as a soil amendment at rates of 10 and 128.0 Mg/ha. The laboratory study *Cook et al. (2012)* determined changes in available water holding capacity, saturated hydraulic conductivity, and bulk density for the biochar application rate of 10 Mg/ha and 128 Mg/ha.

Methods

Model calibration and validation

The Soil and Water Assessment Tool (SWAT) hydrologic simulation model was calibrated and validated for the Spoon River Basin in a previous study that focused on residue removal (Chapter IV). Daily precipitation and temperature data was obtained from National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center *(NCDC, 2010)*. Six precipitation stations (Avon 5Ne, Kewanee 1E, Knoxville, Princeville 2W, Toulon, and Yates city) and two temperature stations (Kewanee 1E and Princeville 2W) were used for the SWAT simulations. Other daily weater data (wind speed, solar radiation, and relative humidity data) was generated by the SWAT weater generator. Figure 5.1 shows monthly simulated streamflows and precipitation in the Subbasin 33 of the Spoon River Basin. Streamflows and sediment yields were calibrated and validated with good results in the previous study. Based on the Nash-Sutcliffe Efficiency (NSE) coefficient values, the model performance for streamflow was good (0.64) for the calibration period (1992 - 2000) and very good (0.83) for the validation period (2001 - 2010). The model performance for sediment yield was satisfactory (0.62) for the calibration period (2004 – 2009).

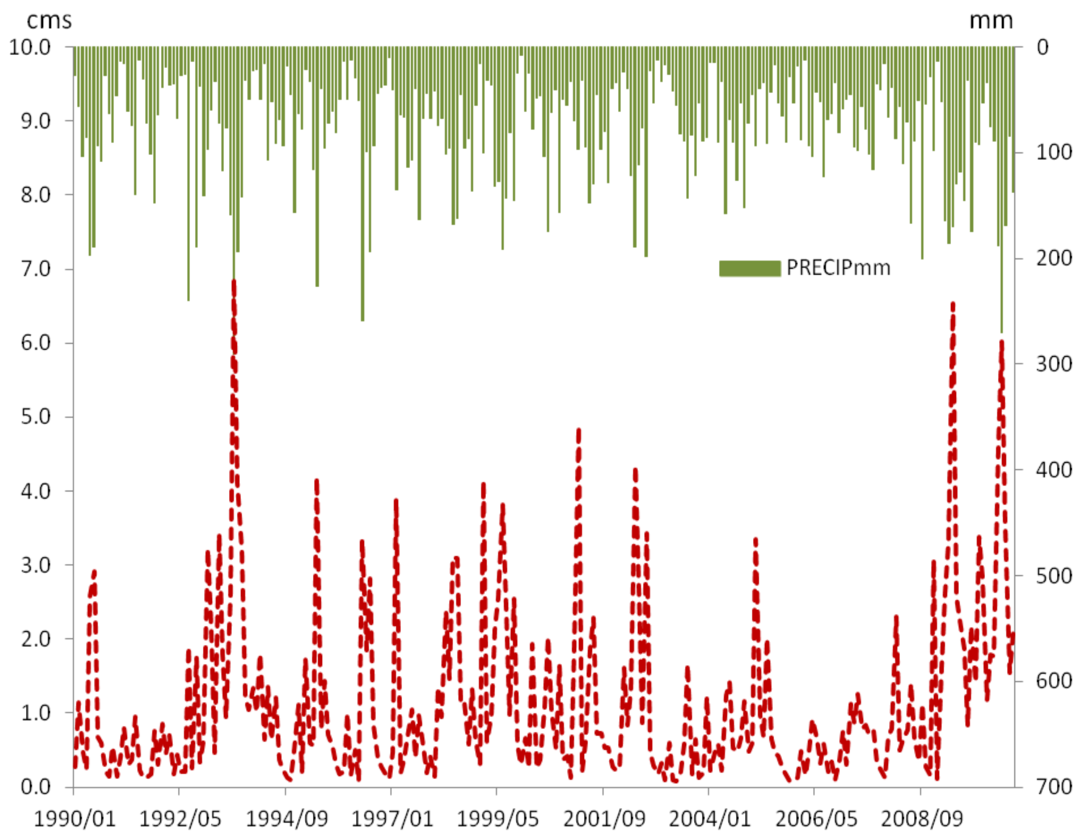


Figure 5. 1 Monthly simulated streamflow and predicitation data in the Subbasin 33 of the Spoon River Basin from 1990 to 2010.

Biochar study

In this study, the SWAT model focused on the hydrologic impacts when biochar was returned to the corn production fields as a soil amendment. Biochar application at the rates of 0, 10 and 128 Mg/ha were simulated in subbasin 33 of the Spoon River watershed planted with corn (shown in Figure 5.2). Subbasin 33 has an area of 57.4 km^2. The size of the corn fields in subbasin 33 where biochar was applied was determined to be 3.20 km^2 for the 10 Mg/ha rate and 0.25 km^2 for the 128 Mg/ha rate.

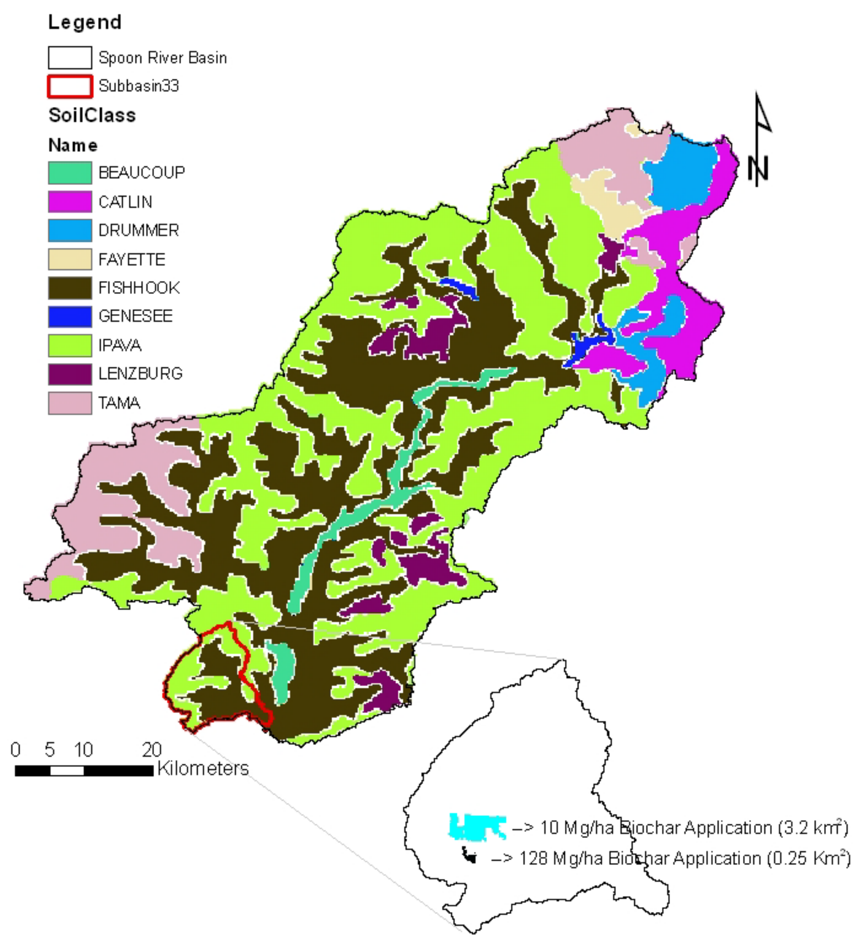


Figure 5. 2 The Spoon River Basin in IL with soil types and the location of subbasin 33 where the biochar was applied to the corn fields at 10 Mg/ha and 128 Mg/ha rates. Subbasin 33 has an area of 57.4 km^2.

The size of the biochar application fields in subbasin 33 was determined as follows. The feedstock rate for a mobile pyrolysis unit was assumed to be 40 tons/day at 10% moisture content. Therefore a total of 14,600 tons of corn stover feedstock could be pyrolyized in one year. In the Spoon River Basin the 10 year (1999 – 2008) average corn yield was 164 bu/ac. Assuming the ratio of corn for grain and corn stover one to one (one bushel of corn was assumed to be 25.4 kg (56 lbs)) *(USDA, 2010b)*, total corn stover availability was determined to be 10,292 kg/ha (9,182 lbs/ac). However, if only 25% of the corn stover was used as a feedstock for pyrolysis and 75% was left for erosion control, then corn stover available for pyrolysis was 2,573 kg/ha (2,296 lbs/ac). Therefore, 51.48 km^2 (12,721 acres) of corn stover would be required per year for one mobile pyrolysis unit. Another assumption was that approximately 22% of the feedstock used in this fast pyrolysis system would end up as biochar *(Dr. Provin, personal communication, 2012)*. Therefore, one mobile pyrolysis unit would produce 3,212 tons of biochar per year. Since subbasin 33 has a total area of 57.4 km^2 (5,740 ha), applying 3,212 tons of biochar at an application rate of 10 Mg/ha requires 321.2 ha and an application rate of 128 Mg/ha requires 25.1 ha (see Table 5.1).

A Texas A&M study of biochar from the pyrolysis system found that the amount of P in one ton of the biochar was 3.04 kg (6.7 pounds) *(Dr. Provin, personal communication, 2012)*. Table 5.1 shows the area required to land apply biochar in subbasin 33 at various application rates and the corresponding P application rates found in the biochar. For this project, biochar applications rates of 0, 10 and 128 Mg/ha were studied.

Table 5. 1 The areas required to land apply biochar in subbasin 33 at various application rates with the corresponding P application rates.

Biochar Application (Mg/Ha)	Area Required (Ha)	Subbasin 33 (%)	Corn Area (%)	P (kg/ha)
5	642.4	4.7	14.6	15.3
10	321.2	2.4	7.3	30.5
20	160.6	1.2	3.6	61.0
32	100.4	0.7	2.3	97.6
64	50.2	0.4	1.1	195.2
96	33.5	0.2	0.8	292.8
128	25.1	0.2	0.6	390.4

In the SWAT simulations, biochar was incorporated into the 0 – 25.4 cm surface soil layer. The predominate soil type in the Spoon River Basin was the Ipava soil. The Ipava soil consists of three layers, a silt loam (soil surface – 25.4 cm), a silty clay loam (25.4 – 127.0 cm), and a silty clay loam (127.0 – 152.4 cm). The Ipava soil has a hydrologic soil group type of B, which has a moderate infiltration rate when wet. For the surface layer of the Ipava soil, available water capacity, saturated hydraulic capacity, and the K factor of the USLE equation were 0.21 (mm/mm), 8.7(mm/hr), and 0.28 , respectively (SWAT database 2009). The management operations used in the SWAT simulations for corn production in Illinois are shown in Table 5.2. The same management operations were used for all biochar application rates. However, the soil hydrologic properties were changed. The simulation of tillage operations was initiated on April 29 with a 15 ft field cultivator. Two different fertilizer applications were simulated using a urea ammonium nitrate (UAN) solution applied at 600 kg/ha and triple super phosphate (TSP) applied at 150 kg/ha on April 30. The same fertilizer applications were applied for biochar applications of 0, 10, and 128 Mg/ha. The dates for planting and harvesting corn were May 9th and October 19th. The planting and harvesting dates were obtained from NASS statistics for IL. The harvest only operations for grain harvest and biomass harvest (25% biomass residue removed) were used in SWAT to apply biochar to soils. A tillage operation (subsoil chisel plow) was implemented on October 21 (after harvesting).

Table 5. 2 Management operations used in the SWAT model simulations of biochar applications to corn fields in IL.

Date		**Management Operation**
April	29	Tillage operation (Field Cultivator Ge 15ft)
	30	Fertilizer application
		Urea Ammonium Nitrate Solution (UAN), 600 Kg/ha
		Triple Super Phosophate (TSP), 150 kg/ha
		Biochar application
May	9	Plant/begin growing season: Corn
October	19	Harvest only operation (grain harvest)
	20	Harvest only operation (biomass harvest)
		- 25% corn stover removed for pyrolysis feedstock
	20	Kill/end of growing season
	21	Tillage operation (Subsoil chisel plow)

Soil and biochar laboratory studies

Laboratory experiments were conducted at Texas A&M to determing changes in saturated hydraulic conductivity (Ksat), water holding capacity (WHC), and bulk density when various levels of biochar were incorporated into soils *(Cook et al., 2012)*. Biochar rates of 0, 32, 64, 96, and 128 Mg/ha were used. Two soils were studied, a Burleson clay and a Booneville loam, and tests were conducted on three dates after incorporation, 0, 45 and 90 days. According to the National Cooperative Soil Survey *(NCSS) (2010)*, the

Burleson soil consists of very deep, moderately well drained, very slowly permeable soils that formed in alkaline clayey sediments. The Booneville soil consists of very deep, well drained soils that formed in slope alluvium and colluvium derived from basalt and welded tuff. The Ipava soil in the Spoon River Basin has soil properties that are closer to the Burleson soil than the Boonevile soil. The available water capacity (AWC) in SWAT is defined as the plant available water (mm H2O/mm soil) in the soil profile. The AWC can be calculated by subtracting the amount of water present at the permanent wilting point (-15 bar) from that amount of water available at field capacity (-0.33 bar) *(Arnold et al., 2011).* A regression analysis was used on the laboratory data for the WHC at -0.33 and -15 bars for the Burleson soil to estimate AWC for the various biochar applications. The WHC for days 0, 45, and 90 were fitted with logarithmic regression curves as shown in Figure 5.3. Using the regression curves, the WHC was calculated to be 0.148, 0.131, and 0.116 for days 0, 45, and 90, respectively for the -15 bar pressure. The AWC was then calculated to be the average of the difference between -0.33 and -15 bar pressure. From this analysis, the AWC increased by 1 % for the 10 Mg/ha biochar application rate and 34 % for the 128 Mg/ha biochar application rate. These changes for AWC were applied to the 0 – 25.4 cm surface layer of the Ipava soil in the SWAT simulations.

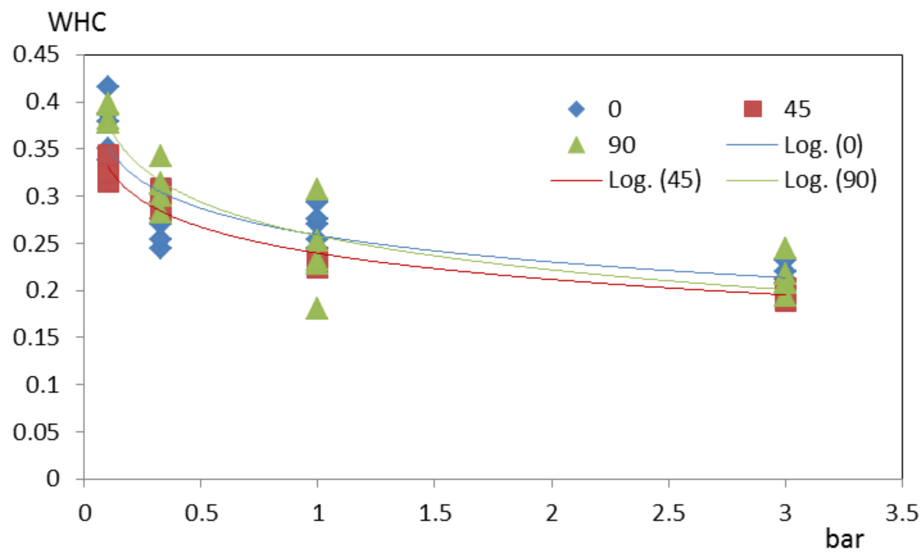


Figure 5. 3 The water holding capacity on days 0, 45, and 90 after biochar incorporation at pressures of 0.10, 0.33, 1.00, and 3.00 bars for the Burleson soil. Also shown are the logarithmic regression curves fitted for each day (Day 0: y = -0.041 ln(x) + 0.2586, R^2 = 0.7621, Day 45: y = -0.04 ln(x) + 0.2394, R^2 = 0.9495, Day 90: y = -0.052 ln(x) + 0.2578, R^2 = 0.8497).

Saturated hydraulic conductivity (Ksat) is defined as the soil water flow rate (mm/hr) when the soil is saturated and is a measure of the ease of water movement through the soil *(Arnold et al. 2011)*. Figure 5.4 shows the average Ksat values as a function of biochar application rate (with error bars) for the Burleson soil for 0, 45, and 90 days after biochar incorporation. Also the regression line fitted to the Ksat data shown in Figure 5.4. Using the fitted regression line, Ksat for the biochar application rate of 10 and 128Mg/ha increased by 15% and 192%, respectively, compared to no biochar application. These changes for Ksat were applied to the 0 – 25.4 cm surface layer of the Ipava soil in the SWAT simulations.

The average bulk density as a function of biochar application rate for 0, 45, and 90 days is shown in Figure 5.5 along with the fitted regression line for the Burleson soil.

Compared to no biochar application for the Burleson soil, bulk densities for biochar application rates of 10 and 128Mg/ha decreased by 1% and 16%, respectively. These changes for bulk density were applied to the 0 – 25.4 cm surface layer of the Ipava soil in the SWAT simulations as well.

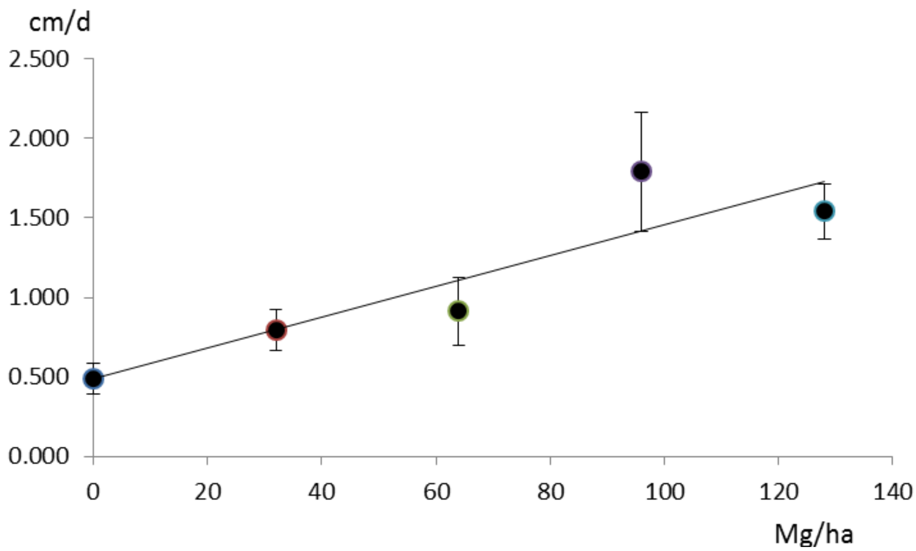


Figure 5. 4 The average Ksat values with standard error bars as a function of biochar application rate for 0, 45, and 90 days after biochar application. Biochar rates of 0, 32, 64, 96, and 128 Mg/ha were used.The linear regression line equation was, y = 0.0097 x + 0.4852(R^2 = 0.8206).

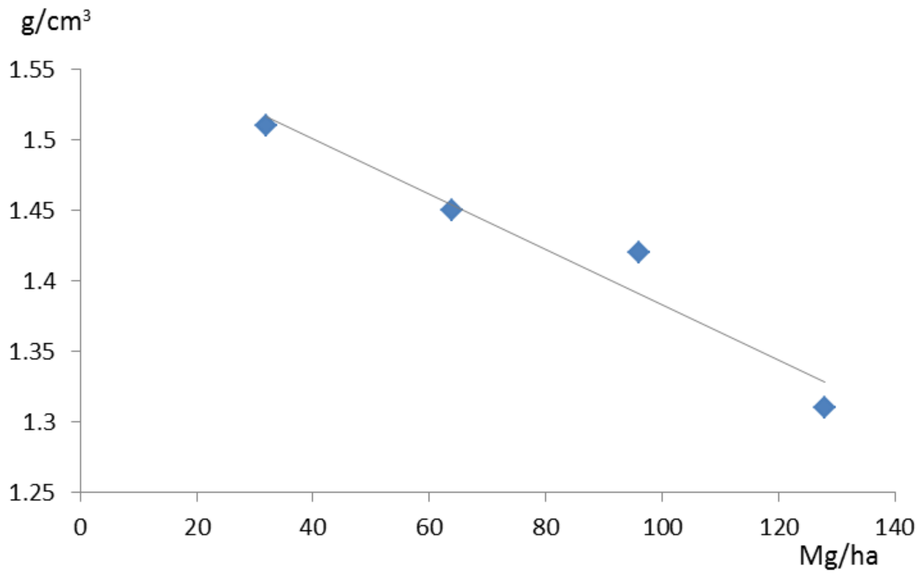


Figure 5. 5 The average bulk density on 0, 45, and 90 days after biochar was incorporated at applications rates of 0, 32, 64, 96, and 128 Mg/ha. in the Burleson soil. Also shown is the fitted regression line, y = -0.002 x + 1.58 (R^2 = 0.9416).

Results

SWAT model simulations

The SWAT model was used to evaluate biochar applications to agricultural soils in the Spoon River Basin in IL. The biochar was assumed to come from a mobile pyrolysis system used to produce bioenergy. The SWAT model was calibrated and validated for simulated streamflows and sediment yields using observed USGS values at the outlet of the Spoon River Basin (Chapter IV). The period of calibration was over 9 years and the period of validation was over 10 years for monthly streamflow. However, sediment yields were only calibrated over 6 years, due to lack of data (Chapter IV). The model performance was evaluated using the Nash-Sutcliffe Efficiency (NSE) statistic. The NSE value for monthly streamflows was 0.66 for the calibration period and 0.84 for the validation period. For sediment yield, the NSE value for model performance was 0.63 and there was not enough data for sediment validation . Overall, the model performance was good or satisfactory for both streamflows and sediment yields. Three different biochar application rates, 0, 10, and 128 Mg/ha, was used in the modeling study. The sizes of the application areas simulated in SWAT were 25 ha for 128 Mg/ha biochar application and 321 ha for 10 Mg/ha biochar application.

Changes in hydrology

From the SWAT simulations, there was very little change for water yields, evapotranspiration, and soil water for the biochar application rate of 10 Mg/ha. For the biochar application rate of 128 Mg/ha, the cumulative monthly water yield (mm) decreased by 5.3% compared to no biochar application. Figure 5.6 shows a comparison of monthly and cumulative water yields (mm) in the Spoon River Basin from 1990 to 2010 comparing no biochar application with an application rate of 128 Mg/ha. The water yield was estimated using the following equation:

$$WYLD = SURQ + LATQ + GWQ - TLOSS \qquad \text{Eq. 5.1}$$

Where, WYLD is the net amount of water contributed by the HRU to the stream reach (mm H_2O), SURQ is surface runoff, LATQ is lateral flow contribution to streamflow, GWQ is groundwater contribution to stream, and TLOSS is stream transmission losses

The cumulative monthly ET rate (mm) for the 128 Mg/ha biochar application rate increased by 1.8% when compared to no biochar application as shown in Figure 5.7. As water yields decreased, ET rates increased when biochar was applied to soils at the

128 Mg/ha rate. This indicates that biochar retained more water in the soil when compared to soils without biochar. The cumulative monthly soil water at the end of month (mm) for the 128 Mg/ha application rate increased by 3.5% when compared to 0 Mg/ha biochar application rate (shown in Figure 5.8). In Figure 5.8, SW_END indicates the soil water content at the end of month (mm H_2O).

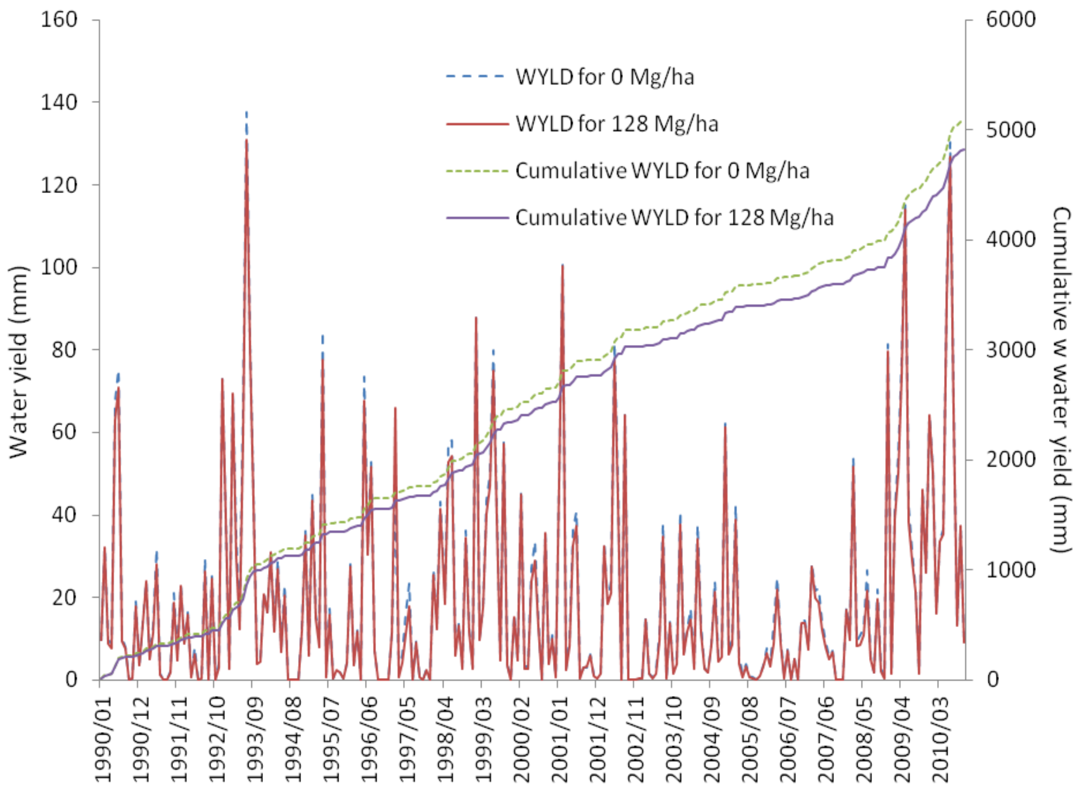


Figure 5. 6 Differences in monthly water yield due to incorporation of biochar at rates of 0 and 128 Mg/ha in a 0.25 km^2 subbasin planted with corn in the Spoon River Basin... The cumulative water yield from 1990 to 2010 is also shown.

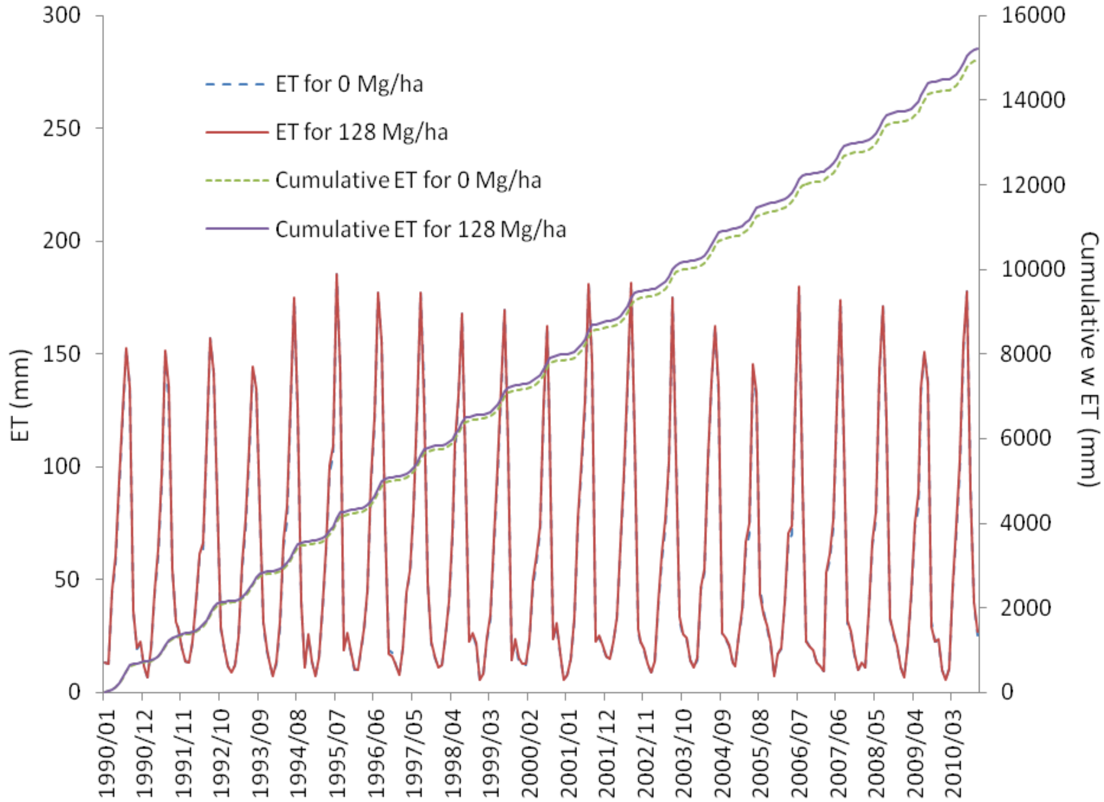


Figure 5. 7 Differences in monthly ET comparing biochar application rates of 0 and 128 Mg/ha in a 0.25 km^2 subbasin planted with corn in the Spoon River Basin. The cumulative ET values from 1990 to 2010 are also shown.

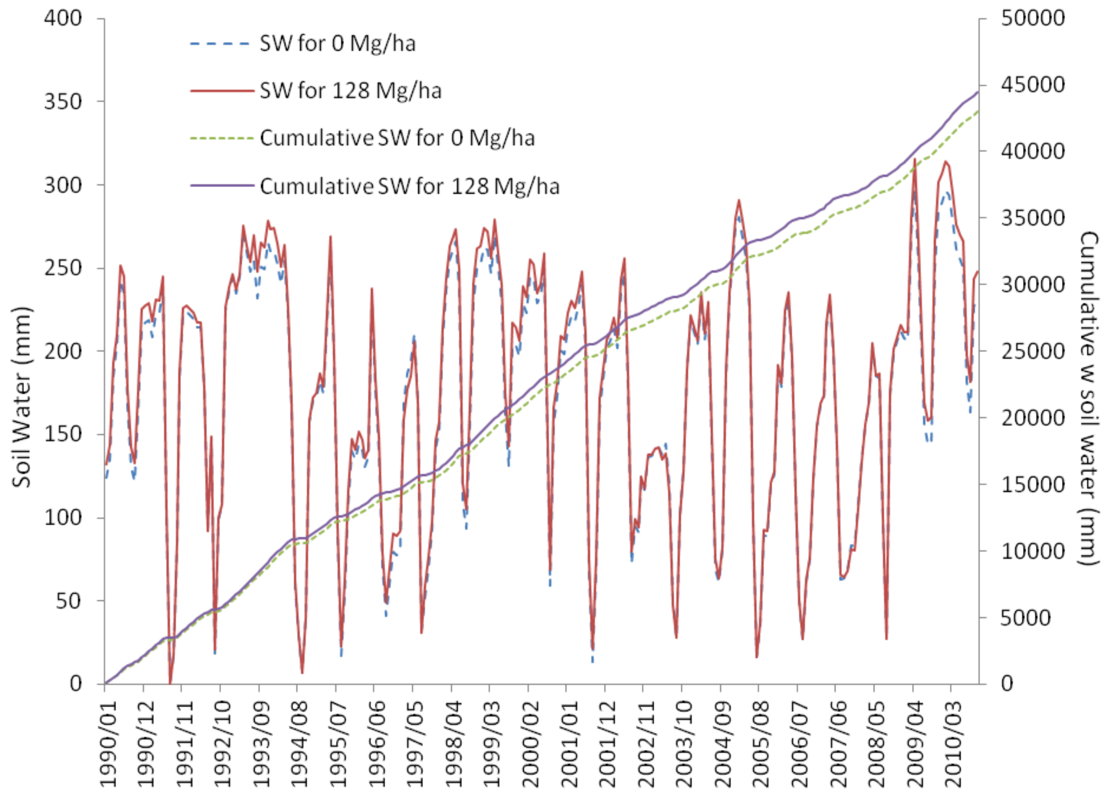


Figure 5. 8 Differences in soil moisture at the end of each month comparing biochar application rates of 0 and 128 Mg/ha in a 0.25 km^2 subbasin planted with corn in the Spoon River Basin. The cumulative soil moisture values from 1990 to 2010 are also shown.

Changes in sediment losses

The cumulative monthly sediment yield (t/ha) decreased by 5.6% for a 0.25 km^2 watershed planted with corn that received the 128Mg/ha biochar application when compared to no biochar application rate. Figure 5.9 shows the monthly and cumulative sediment yields comparing the 0 and 128 Mg/ha application rate in the Spoon River Basin from 1990 to 2010. According to the Web Soil Survey (WSS) *(USDA NRCS, 2011)*, the average T factor is 5 t/ac (12.4 t/ha) per year for the Spoon River Basin. As shown in Figure 5.9, the sediment yields did not exceed the soil loss tolerance factor over the simulation period in the Spoon River Basin. One potential negative effect of residue removal is increased soil loss. However, the sediment yield actually decreased when the biochar was applied at a rate of 128 Mg/ha to the soils. As shown in Figure 5.10, the average monthly sediment yields comparing no biochar application to the 128 Mg/ha biochar application rate indicate that sediment yields decreased during the growing season in the Spoon River Basin.

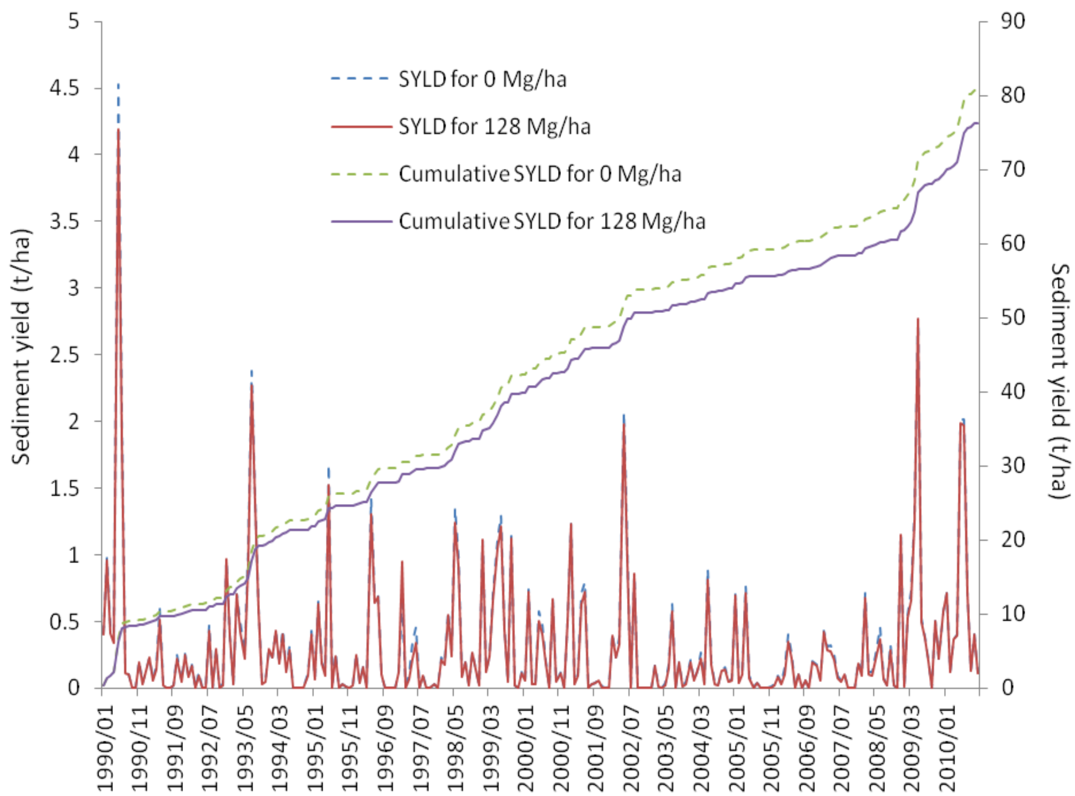


Figure 5. 9 The monthly sediment yields comparing biochar application rates of 0 and 128 Mg/ha in a 0.25 km^2 subbasin planted with corn in the Spoon River Basin. The cumulative erosion rate from 1990 to 2010 is also shown.

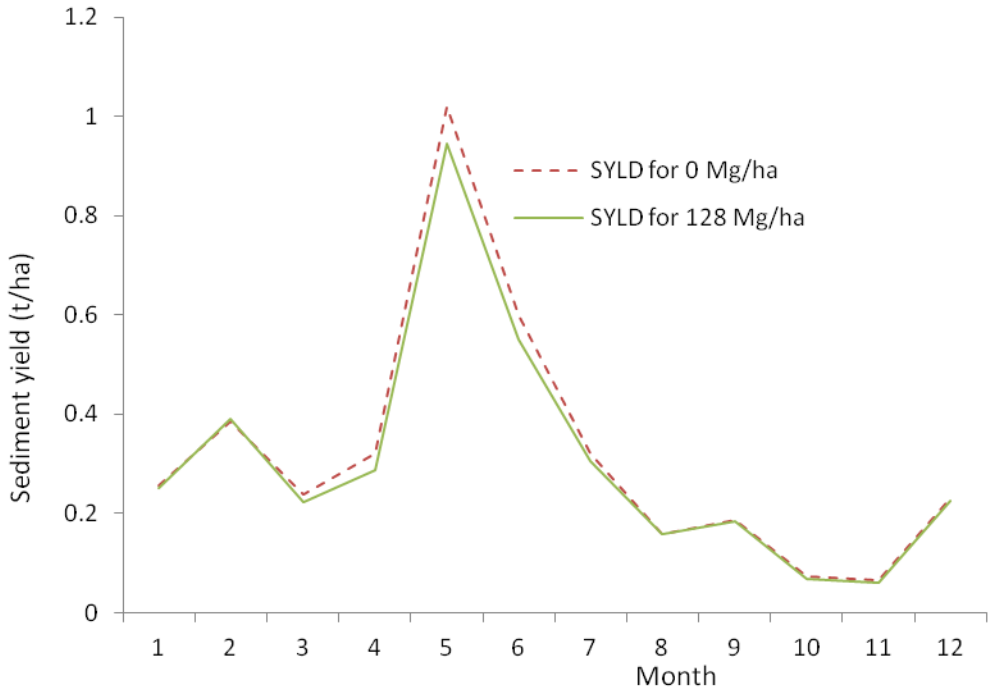


Figure 5. 10 The average monthly sedimet yields from 1990 to 2010 comparing biochar application rates of 0 and 128 Mg/ha in a 0.25 km^2 (25 ha) subbasin planted with corn in the Spoon River Basin .

Conclusion

The mobile pyrolysis system converts diverse feedstock sources to bio-oil, synthesis gas, and biochar. Recycling the biochar to agricultural fields as a soil amendment for cycling nutrients and earning carbon credits is required for a sustainable bioenergy system. The SWAT model was used to assess hydrologic changes due to biochar applications to corn fields in the Spoon River Basin in IL. Corn stover in the Spoon River Basin would be an excellent feedstock for mobile pyrolysis and the biochar could be recycled back to the feedstock production fields.

Biochar is a low density carbon-based material that can improve soil properties and retain water and nutrients. Laboratory experiments were conducted by *Cook et al.*

(2012), to determine soil property changes due to biochar incorporation on a Burleson clay and a Booneville loam soil. A major soil type in the Spoon River Basin is an Ipava soil, which is similar to the Burleson clay. Three biochar application rates, 0, 10, and 128 Mg/ha, were simulated in the Spoon River Basin. The Ipava soil properties for AWC, Ksat, and bulk density were adjusted based on the laboratory experiments by *Cook et al. (2012)*. AWC was increased by 1% and 34% for the 10 and 128 Mg/ha biochar application rates, respectively. Ksat was increased by 15% and 192% for the biochar application rates of 10 and 128 Mg/ha, respectively. Bulk density was decreased by 1% and 16% for the 10 and 128 Mg/ha biochar application rates, respectively. The calibrated and validated SWAT model with modified soil properties due to biochar incorporation was then used to evaluate changes in hydrology, sediment losses, and nutrient transport after biochar was applied to soil.

There were no discernible changes between the 0 and 10 Mg/ha biochar application rates. However there were changes between the 0 and 128 Mg/ha biochar application rates. For stream flows, water yield decreased when soil water and evapotranspiration (ET) increased comparing no biochar application with an application rate of 128 Mg/ha. Biochar retained more water in soil with biochar application (128 Mg/ha). Reductions in water yield were attributed to reduced sediment yield, caused by increases in ET. With a biochar application at the rate of 128 Mg/ha, sediment yields also decreased during the growing season in the Spoon River Basin. The tolerance factor (T factor) for sediment yields is 5 t/ac (12.5 t/ha) in the Spoon River Basin, and was not exceeded in the area where biochar 128 Mg/ha applied. Therefore, biochar had beneficial impacts as a soil amendment and can contribute to sustainable biomass production by reducing soil erosion.

CHAPTER VI

SUMMARY

A GIS program was developed to optimize the use of mobile pyrolysis units to produce bio-oil from corn stover, energy sorghum and swtichgrass in the North Central region. This GIS program was based on an analysis of transportation networks, crop patterns and production rates, and oil refinery locations. Feedstock input rate for one mobile pyrolysis unit was 40 tons/day. A major strength of the mobile pyrolysis unit is its flexibility. The GIS analysis calculated the grid size, feedstock and biochar transport distances from feedstock production fields to the mobile pyrolysis units, and short distances from one mobile pyrolysis station to the next station. The shortest distance between mobile pyrolysis stations and the optimum route from the pyrolysis station to the nearest oil refinery were also determined using Network Analysis. Model builder made is possible to automate the GIS procedures.

Feedstock logistics were evaluated for move times of 1 to 12 months for mobile pyrolysis units. The harvest grid sizes ranged from 2.4 to 9.6 km, from 5 to 23 km, and 3.3 to 12 km for corn stover, energy sorghum, and swtichgrass, respectively. When all feedstock were pyrolyzed in Illinois and Nebraska, corn stover, energy sorghum and swtichgrass needed 853, 73, 159 mobile pyrolysis units. The GIS program was integrated with an economic model to assess bio-oil production costs. The economic model results indicate that a 12 month move time has the highest probability of success, but there might be some constraints such as weather condition and feedstock availability.

As bioenergy from feedstocks is produced, the removal of biomass from agricultural areas might impact the hydrology and sediment transport in rural watersheds. The SWAT model was used to evaluate streamflow, sediment yield, and crop/biomass yields in the Spoon River basin in IL to ensure that the mobile pyrolysis method for bio-oil production was environmentally sustainable. The hydrologic impacts of residue management practices that removed 0%, 25%, 50%, 75% and 100% of the residue were investigated. The SWAT model was calibrated and validated for streamflow and sediment yields in the Spoon River basin based on observed streamflow and sediment yield data from the USGS gauging station (0557000). When the residue removal rates increased, streamflow slightly decreased, evapotranspiration (ET) increased, and sediment yield increased. The residue removal rates were related to soil erosion, and the tolerance factor, 5 tons per acre per year, was exceeded at the 75% removal rate in the Spoon River basin.

Biochar is a carbon-based byproduct from the pyrolysis process. As much as 22% of the feedstock used to produce pyrolysis bio-oil ends up as biochar. Biochar must be land applied to feedstock production fields as a soil amendment for agronomic and economic profit. The SWAT model was used to assess hydrologic changes due to the land application of biochar based on changes in soil properties (water holding capacity, saturated hydrologic conductivity, and bulk density) from laboratory experiments by Cook et al. (2012). Two different biochar rates , 10 Mg/ha and 128 Mg/ha, were applied to feedstock fields. When a biochar application rate 128 Mg/ha was applied to fields, water yield decreased; sediment yield decreased; soil moisture increased; ET increased.

Therefore, biochar had useful impacts as a soil amendment and reduced soil erosion contributing to sustainable biomass production.

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